

IDRISS AUDU

**Development and application of runoff model for
water harvesting in North East Nigeria**

Institute of Water and Environment

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Cranfield University

Institute of Water and Environment

PhD

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Idriss Audu

**Development and application of runoff model for water
harvesting in North East Nigeria**

Supervisor: Dr. T.M. Hess

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**This thesis is submitted in total fulfilment of the requirements for the
award of degree of Doctor of Philosophy**

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DEDICATION

To my children FATIMA, AISHATU and ABDU

ABSTRACT

Rainfall in the northeast arid zone of Nigeria is limited and has been found to be declining over the last three decades (Hess et al., 1995). This problem of inadequate rainfall is further exacerbated by runoff especially on the degraded lands (*fako*). Such runoff-prone lands are potential areas for water harvesting. In dry years, harvested runoff water can considerably improve the environmental conditions for plant growth and can make the difference between death and survival. However, water conservation techniques will only show a benefit if the soil is able to hold the extra water within the root zone of the crops. A clear understanding of soil properties and moisture variations on these lands should provide the baseline information needed for applied soil and water management research.

Aerial photographs and photo mosaics were used to identify several *fako* lands out of which three sites were selected for detailed study. The three sites were located at Jawa (12° 48.71' N, 11° 02.21' E), Zurkaya (12° 49.15' N, 11° 05.52' E) and along Dumburi road (12° 54.31' N, 11° 07.49' E). The *fako* lands have compacted loamy and clay loamy soils with low infiltration rate and hydraulic conductivity. Dry bulk density values range between 1.34 gcm⁻³ to 1.61 gcm⁻³ and saturated hydraulic conductivity obtained were between 1 mm/h and 6 mm/h. Water retention characteristic curves revealed that the *fako* soils have good water holding capacity. Slopes are generally gentle and range from 0.1% to about 1%.

Volume of water harvested depends on the runoff yield of an area. Models can be used to estimate runoff on the *fako* lands. The model to be used will depend upon the available information, the required accuracy and the resolution of the output and the time resources that can be directed at the modelling exercise. As the rainfall data available for the area is in daily time step, a model that can use daily rainfall as input to estimate runoff is required. In order to develop such a model, accurate rainfall-runoff records for several years should be obtained. High-resolution rainfall data for 13 site-years were collected between 1992 and 1994. The EUROSEM model

(Morgan et al., 1992) was applied to simulate the rainfall events and partition them into overland flow and infiltrated water. The model was however calibrated and validated before being used for the simulations. For the calibration and validation, a rainfall simulator (USDA, 1972) was constructed and 32 rainfall-runoff events at intensities of between 25 mmh^{-1} and 169 mmh^{-1} were artificially generated on the three sites. A graph of measured versus simulated runoff events showed good agreements in both calibration and validation. Coefficients of determination and efficiency were 0.82 each in calibration and 0.83 and 0.74 in validation.

Predicted runoff by the EUROSEM model was regressed against daily rainfall to obtain a linear regression model for predicting runoff from daily rainfall for the *fako* lands of north-east Nigeria. The model can be regarded as an integral expression of the physiographic and climatic characteristics that govern the relations between rainfall and runoff on the *fako* areas. Runoff coefficient and threshold value obtained for the area were 0.44 and 16 mm respectively. The linear model was compared to the curve number model and the runoff estimates by both models were similar.

The developed linear model was combined with a water balance model, BALANCE (Hess, 1994) and applied to microcatchment water harvesting investigations. The BALANCE model was used to estimate the water balance components for the area. The Ritchie equation in the BALANCE model was calibrated and validated with field data. Measured versus predicted soil moisture plot gave R^2 values of 0.90 and 0.89 in calibration and validation respectively. Growth of neem tree (*Azadirachta indica*) on a typical *fako* land was simulated with different microcatchment sizes in three categories of years (dry, average and wet). Simulation results indicated that augmenting rainfall through runoff water harvesting technique could provide enough water to sustain growth and ensure rapid establishment of the neem tree seedlings. However, due to reduced dry spell some deep percolation may result during the peak of the rainy season (August – mid September) especially in wet years. A microcatchment size of 12m^2 (basin-runoff area ratio of 1: 2) was found to sustain year round survival of the tree and minimum drainage for all categories of years.

Complementary to water harvesting in the conservation measure, effect of three soil cover treatments (bare, perforated polyethylene cover and solid polyethylene cover) on soil evaporation was investigated. As expected, the solid cover was found to have the most effect in reducing soil evaporation but this is not suitable in the current situation because it limits infiltration of rain and free air circulation. The perforated cover treatment is preferred as it can also significantly reduce soil evaporation and at the same time allow unrestricted infiltration of rain and free exchange of gases between the soil and atmosphere.

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CHAPTER ONE

INTRODUCTION

1.1. BACKGROUND

Due to increase in population and low crop yield as a result of limited rainfall over the past years, the upland area of the North East Arid Zone of Nigeria is under pressure as the farmers cultivate more lands in order to meet their needs. The climatic conditions of this zone are such that it is very difficult for annual crops and other plants to grow. The natural regimes of climate, water and vegetation in this region are dynamic and highly variable.

The potential production capacity of the land and its component soils and natural resources has declined over the years. The decline is as a result of a number of factors, some of which include soil degradation (Lal, 1988) and reduced rainfall (Hess et al., 1995). Soil degradation implies the decline in soil quality and productivity brought about by physical, biological and chemical processes. These processes result from erosion, desertification and nutrient imbalance. The FAO (Lal, 1988) has estimated that over 85 per cent of Africa north of the equator is vulnerable to accelerated erosion, the causes of which are overgrazing, deforestation and intensive cropping. The deterioration of these areas owing to overgrazing, clearing and drought is a major cause of desertification in the Sahel (Timberlake, 1985; Grainger, 1982).

Due to the extreme climatic irregularities, some of the initial problems that the farmer needs to solve are that of providing water to his annual crops and that of good grazing lands for his animals. There is need to harness and conserve the limited available water resources and maximize the benefit from the uncertain and erratic distribution of rainfall. In the Sahel, it has been estimated that between 200-500 million m³ of water are lost annually through runoff which could be used to irrigate about 20,000-40,000 ha (Ben-Asher, 1988).

1.2. THE NORTH EAST ARID ZONE DEVELOPMENT PROGRAMME AREA

Under the sixth European Development Fund of the 'Lome 3' agreement, the European Community (EC), working in partnership with the Federal Government of Nigeria (FGN), set out to develop an integrated rural development programme. As a result, the North East Arid Development Programme (NEAZDP) was established to address environmental, economic and technical problems.

The NEAZDP area lies within the Sudano-Sahelian Zone of Northern Borno and Yobe states of Nigeria (figure 1.1) and covers an area of about 25,000 km² with a population of about 1.2 million inhabitants. The Yobe river drains the NEAZDP area including vast areas of the Jos highlands upstream and empties into Lake Chad. The area is generally flat with plains gently sloping from the uplands towards the river. The area is covered by sparse vegetation of shrubs and scattered trees with denuded areas and small depressions.

The area chosen for this study lies in the central part of the NEAZDP area and it covers an area of about 2053 km². It includes the uplands and floodplain of the Yobe river. Aerial photographs and photo-mosaics of November 1990 indicate that about three per cent of the uplands in the area selected for the present study is barren and degraded. These barren areas support little or no vegetation probably as a result of the seemingly low infiltration capacity of the soil and its accompanying high runoff. According to Abdalla (1994), there has been an increase in unproductive lands in the north east arid zone of Nigeria caused by overgrazing and reduced rainfall over the years.

Chapter 1

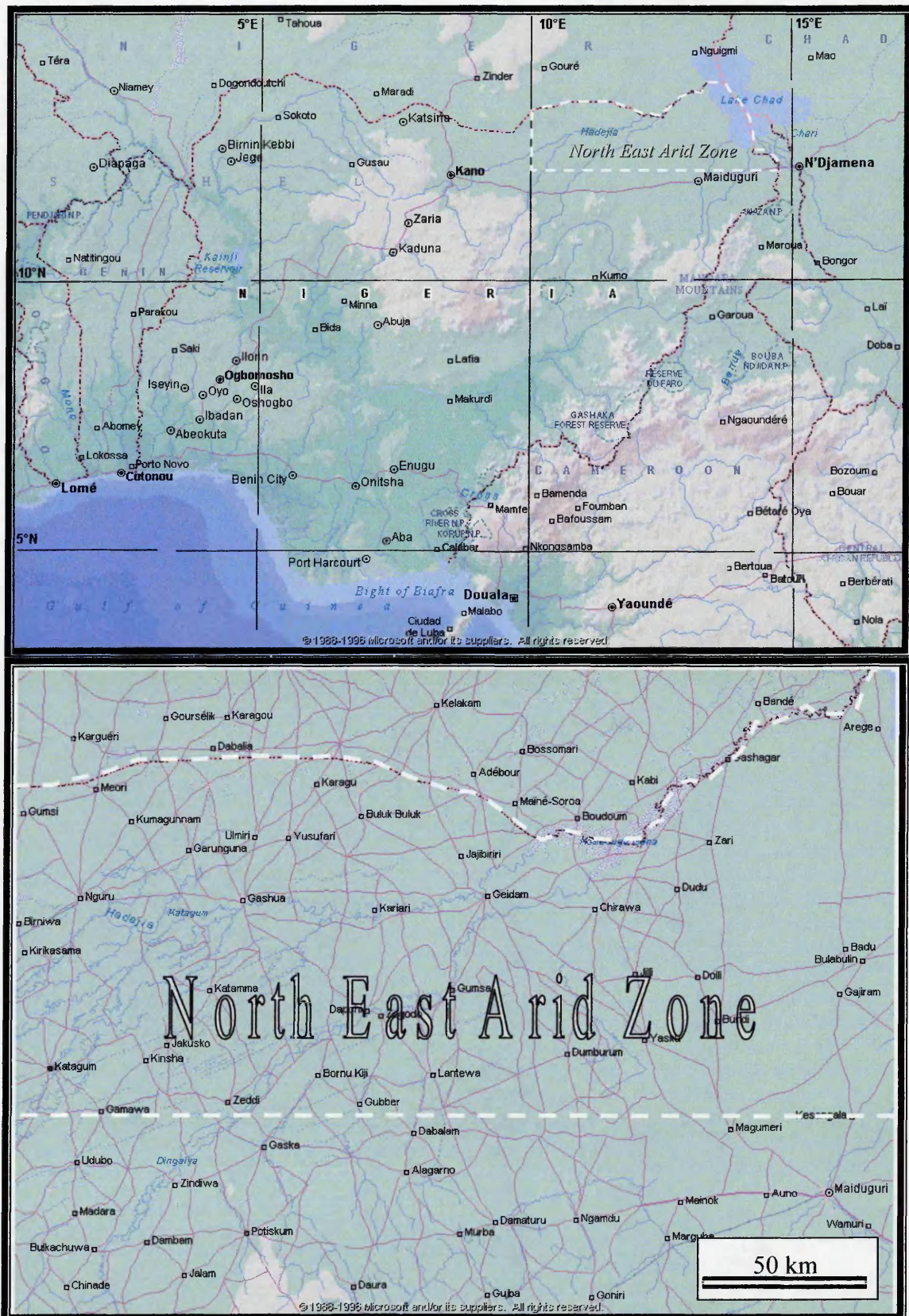


Figure 1.1: Map of Nigeria showing the approximate NEAZDP area.

People in the area use the following local terms to describe four distinct land systems:

- a) “*tudu*”: upland farmland on stabilized sand dunes dominated by light freely draining sandy soils that are commonly used for millet/sorghum cropping.
- b) “*fako*”: these are degraded areas that support little or no vegetation and are prone to runoff and are usually found on the downslope sides of the *tudu*. The soils are very hard and the farmers do not cultivate this land.
- c) “*tapkis*”: these are wet interdunal depressions that are seasonally flooded and may provide water for livestock in the dry period. The soils are predominantly clay and in some places may crack when dry
- d) “*fadama*”: seasonally flooded areas along the shores of the river are locally called *fadama*. Farmers use irrigation and residual moisture to cultivate this rich alluvial soil for the production of vegetables and fruits.

The long term mean annual rainfall (1961 - 1990) of this area ranged from 660mm in the south west, to 340mm in the north east, although it has been shown to be declining over this period (Hess et al., 1995). The published mean for Gashua (latitude 12° 53’’ N and longitude 11° 02’’ 30’ E) is 420 mm (NEAZDP, 1991). Most of the rains fall between July and September and rainfall events are characterised by high intensities. According to Kowal and Kassam (1976), the peak intensity may be as high as 200-mm h⁻¹. As a result of the high intensity rain, runoff is a common feature especially on the degraded areas. In a catchment in Northern Nigeria, Kowal (1970) estimated that more than 20 per cent of the rain might be lost as runoff.

The mean daily temperature is more than 26 °C accompanied by high incoming solar radiation with maximum and minimum values at Nguru (12° 53" N, 10° 28" E) of 20.7 and 15.7 MJm⁻²d⁻¹ respectively (Alhassan 1996). Except during the rainy season, the relative humidity is generally low. Wind speed is moderate to high. Potential evapo-transpiration far exceeds rainfall. According to Schultz (1976), the mean annual evaporation for Nguru over a 10 year period, calculated according to Penman method is 2674 mm per annum. This is in slight disagreement with the range of values given by Hess (1998) (4mm/day in the months of December and January and 7mm/day in April).

1.3. DEFINITION OF THE PROBLEM

It is widely held that water is one of the most limiting factors of crop production in the semi-arid tropics (IFAD, 1992; Huibers and Stroosnijder, 1992) and the Sahel in particular (Mortimore, 1989). The inadequacy of rainfall poses a serious constraint to crop production in the NEAZDP area. The problem of inadequate rainfall for crop water supply is exacerbated by runoff. Not only is the limited water supply reduced, there is also an accompanying erosion of the topsoil which tends to crust and reduce soil fertility. Reduced soil fertility results in less biomass production and consequently, less surface cover and less soil macrofaunal activity and high runoff.

For the past two decades, the authorities in Nigeria have been engaged in tree planting programme in the north east arid region but with little success. The degraded areas are deliberately targeted with the aim of at least checking the encroachment of the Sahara Desert. Neem (*Azadirachta indica*) seedlings are grown in the nursery and then transplanted on to these areas. Most of the transplanted seedlings die during the dry season presumably due to lack of water. Only a few of the seedlings survive, and the few that survive are usually found in the lower areas or small depressions of the land where a sort of natural water harvesting takes place during the rains.

Simple and cheap ways of water harvesting and conservation that can be readily adopted by the people should be sought. One of the ways to improve the supply of water for crop production in the north east arid zone is through conservation and efficient utilization of the limited available water supply (precipitation). However, water conservation techniques will only show a benefit if the soil is able to hold the extra water within the root zone of the crops. Where the available water capacity of the soil is low, or the rainfall events are closely spaced, encouraging extra infiltration may only result in increased drainage losses. A clear understanding of soil properties and moisture variations on these lands should provide the baseline information needed for applied soil and water management research with the objective of making efficient use of the limited water resources.

1.4. AN OVERVIEW OF NEEM TREE

The neem (*Azadirachta indica*) or Indian Lilac originates probably from Burma and is now widespread in India, the Sahel region of Africa and Central and South America. In India it has been cultivated for thousands of years, and it was introduced to many African countries by colonial governments. Neem trees are easily grown in warm, frost-free areas and are relatively fast growing. The tree is propagated from seeds, saplings or tissue culture and will require rainfall of 400-1200 mm and can withstand temperatures of 50°C. Other species of neem are *A. siamensis*, found in Thailand, and *A. excelsa*, found in remote areas of Malaysia and the Philippine islands.

The neem is a multipurpose tree ideal for reforestation programmes and for rehabilitating degraded semi-arid and arid lands. It has the ability to grow in hostile sites and produce dense shade for man and animal. Neem tree can survive with 150mm of rainfall and optimal development can be achieved with rainfall of between 450mm to 750mm but it is sensitive to flooding (Von Maydell, 1983). It can develop roots down to 15m and grow up to 15 m tall and also can live for up to 200 years (NEEMAURA, 1999). The neem has various uses in several areas ranging from

agriculture (Barnajee, 1994), environment, pharmaceuticals (Abatan and Mahinde, 1986; Alam et al., 1989; Badam et al., 1987) and commerce (NEEMAURA, 1999).

When research on neem started at around the 1920's, several compounds were isolated from its seeds. One of these, azadirachtin, was found to both repel and disrupt the growth and reproduction of many destructive insect species. The range of insects affected by neem extracts includes beetles, flies, mosquitoes, caterpillars, locusts and grasshoppers, aphids, weevils and moths (NEEMAURA, 1999)

Many people brush their teeth daily with neem twigs. Dentists confirm that this practice guards against periodontal disease. In India, it is mainly used to produce crude antiseptic soap made from the pulp of the fruit. A paste, made from the leaves, has been found to successfully treat skin lesions. Small portions of leaves mixed with regular feed seem to affect intestinal parasites in livestock.

In many areas of Third World countries, wood of any kind is at a premium. Neem timber has been shown to be rot and insect resistant. The oil is clean burning, and the tree produces excellent firewood.

Perhaps the most important trait of neem is its ability to persist and grow in drought-prone soils. Many areas of Africa have suffered from overgrazing and subsequent desertification. Re-forestation efforts have been greatly aided by the introduction of neem trees to these areas. In the Majjia valley of Niger Republic, more than 500 km of windbreaks comprising double rows of neem trees have been planted to protect millet crops which resulted in 20 % increase in grain yield (Benge, 1988).

1.5. SIGNIFICANCE OF WATER HARVESTING

In arid and semiarid regions, water harvesting can be a source of water for a variety of purposes when normal sources of supply fail. Rainwater harvesting has been defined as a method for inducing, collecting, storing and conserving local surface runoff for agriculture in arid and semi-arid regions (Boers and Ben-Asher, 1982). In addition to providing supplemental water for growing food and fibre crops, water harvesting systems can supply drinking water for people, livestock and wildlife. In

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some areas, precipitation collected from the roof of houses provides a household water supply.

In a water harvesting system for agriculture, the rainfall induces surface flow on the runoff area which flows down the lower end of the slope where it is collected in the basin area (also called run-on area). Most of the water in the basin area infiltrate into the soil and is stored in the root zone (Ben-Asher, 1988; Simiyu et al., 1992). In dry years, the harvested runoff water can considerably improve the environmental conditions for plant growth and can make the difference between death and survival. Runoff harvesting can also reduce soil erosion by controlling the surface flow, and can recharge groundwater through deep percolation in wet years.

Water harvesting system must be individually designed to fit the needs and conditions of a specific site and use. Some of the factors that determine the design and type of water harvesting system include; the time distribution of the required quantities of water, rainfall quantity and frequency, soil characteristics and topography, catchment runoff efficiency and cost of construction of the system.

Evanari et al. (1961) documented some of the earliest agriculture in the Middle East. 'Wadis' were used in the Negev desert of Israel for agricultural purposes. Pacey and Cullies (1986) and Critchly & Reij (1989) reported of techniques used in harvesting rainwater. Cisterns and micro-catchment techniques were used for storing water for domestic use of both man and animal, and tree growth respectively. Stone lines, earth bunds, pitting and planting pits, have been used in Burkina Faso, Mali, and Kenya to grow crops like sorghum, millet and maize (Roose, 1990; IFAD, 1991; Ayers, 1989; Simiyu et al., 1992). Rangeland management through the application of water harvesting techniques was reported to have produced good results in Australia (Keetch, 1981; Sudan (Hays, 1981) and Arizona (Martin and Ward, 1970).

As a result of the low rainfall and drought in the sub-Saharan Africa, a number of water harvesting projects started to be developed in the early 1980's to improve crop production and reduce the effect of the drought. In the Yatenga region of northern part of Burkina Faso, a number of micro-catchments of the contour bund type were

successfully tried. The Katumani pitting technique in Kenya has been tried and found to be successful in rehabilitating degraded grazing lands (Simiyu et al., 1992). Audu and Hess (1994) reported that computer simulation studies with agro-climatic model predicted benefits of runoff harvesting to upland millet systems in the north east arid zone of Nigeria especially during dry spells. However, in a semi-arid region of Kenya, Stephens and Hess (1999) used the PARCH model (Hess et al., 1997) to model the benefits of soil water conservation and reported that there is no universal benefit to be gained from soil water conservation measures. According to them, water is not limiting in wet years and therefore, water conservation offers little benefit, and in drier years there is little rainfall to runoff and harvest.

In their study at Jawa, near Gashua, Folorunso and Dunham (1993) assessed the scope of alternative water conservation strategies such as inter-cropping and rainwater harvesting through appropriate land-shaping techniques for maximizing utilisation of rainfall by crops. They simulated benefits derivable from runoff harvesting using a water management and crop production simulation model SWATRE (Belmans et al., 1983). In their simulation, they assumed 20% runoff, which is not unusual for sahel soils (Huibers and Stroosnijder, 1992). They concluded that runoff harvesting could enhance cumulative infiltration of rainwater and hence greater water availability to crop.

A preliminary field trial at Zurkaya was carried out to test the possibility of water harvesting on the *fako* lands. Fodder species (mixture of stylo and gamba grass seeds), tree seedlings (*Acacia nilotica*) and conventional cowpea were tested in banded plots. For the tree seedlings, the effective microcatchment size for each tree was about 6 m². Cowpea was planted parallel to the bands at a density of 2 seeds per hole and the grass seeds were broadcast over the plots. Details of this trial are present as an annex to chapter seven. The trial indicated that water harvesting structures (bands) can stimulate the revival of natural vegetation and crop growth by retaining the runoff on gently sloping *fako* land which would otherwise be lost. Growths of the plants in the lower parts of the plots (where water concentrates) were better than in the upper parts of the plots. This characteristic (where only some part of the plot is

used for cropping) implies that only high value crops with careful consideration of possible water-logging may be suitable for the area.

With the positive indications of water harvesting in enhancing crop growth, the strategy can be employed and extended to the tree planting programme with a view to reducing the mortality rate of the seedlings and improve the result of the programme.

1.6. RUNOFF MECHANISM

Runoff usually means surface flow. It is that portion of the precipitation that makes its way towards channels, streams, lakes or oceans as surface flow (Schwab et al., 1993). In arid and semi-arid regions, the predominant runoff mechanism is Hortonian (Dawdy, 1991). Runoff occurs only when the rate of precipitation (intensity) exceeds the rate at which water infiltrates into the soil (Horton, 1940) and the surface depressions are filled. If the rainfall intensity exceeds the limiting soil moisture content, the pore water pressure at the soil surface will reduce to zero, thereby allowing ponding to take place (Morgan, 1986). Although water table is usually deep in the arid and semi arid regions, a temporary saturated hydraulic condition may occur during storms and water movement and interactions take place in a shallow surface layer.

1.6.1 Factors Affecting Runoff Generation

Runoff is affected by two major factors; climate and catchment characteristics.

Climatic Factors

The main climatic factors that affect runoff are rainfall and evapo-transpiration. Rainfall affects runoff in terms of its intensity and duration. High intensity rains cause large runoff. High intensity rainfall is generally associated with big drop sizes and high drop velocities (Laws and Parsons, 1943) and hence high kinetic energy that compacts soil and reduces infiltration on impact. Reduced infiltration will shorten time to ponding and thereby increase runoff volume.

There is a clear relationship between total runoff for a storm and the duration for a given intensity, though it is reported that duration and intensity themselves have some relationship (Hudson, 1971). Long duration rains are mostly of low intensities while high intensity rainfalls only last for a short time (Hudson, 1971). A storm of short duration may produce no runoff, whereas a storm of the same intensity but of long duration will result in runoff. A prolonged storm of low intensity saturates the soil and results in a decrease in infiltration with time and subsequently generates runoff.

Evapo-transpiration is a combination of evaporation and transpiration, and is a function of temperature, humidity, wind speed and solar radiation. While evaporation is the transfer of water from the surface of the soil to the atmosphere, transpiration is the transfer of liquid water from living plants to the atmosphere. Evapo-transpiration increases with temperature, wind speed and solar radiation but decreases with increase in humidity. For a given rainfall and soil condition, an increase in evapo-transpiration will decrease runoff as is described by equation 1.1 (Shanan and Tadmor, 1979).

$$R = P - S - I - E - C \quad (1.1)$$

where,

R = runoff

P = precipitation

S = depression storage

I = infiltration

E = evapo-transpiration

C = interception

Catchment characteristics

Soil texture, vegetation cover and topography are the catchment characteristics that play important roles in determining runoff. Soil texture determines the infiltration

rate and other hydraulic properties of a soil and thus exerts a major control over the generation of surface runoff. One of the most important factors influencing rainfall - runoff relationship is the infiltration capacity of the soil. Sandy soils have higher infiltration rate at any point in time than heavy textured soils and therefore, generate less runoff for a given rainfall.

The soils of the *fako* lands are generally clay loam in texture. Such soils are prone to capping or crusting especially in areas of high intensity rains. It has been shown that soil crust reduces infiltration, and reduction in infiltration results in increase in runoff (Hillel, 1980). The process of crust formation commences when there is breakdown of soil structure caused partly by the beating action of raindrops and partly by an assorting action of the water flowing over the surface. The fine particles are fitted around the larger ones to form a relatively impervious seal and a significant reduction of soil infiltrability results (Roth and Helming, 1992).

The slope of a catchment has a major effect on the rate of runoff and the peak discharge rate at downstream points, but have little effect on how much of the rainfall will run off. In their study of the effect of slope on runoff in Burundi, El-Hassanin et al. (1993) found out that runoff-rainfall ratios were always high under the steep slopes, but as slope length increased from 5 to 20 m, the runoff-rainfall ratio decreased.

Vegetation cover affects runoff through the processes of evapo-transpiration, interception and overland flow velocity reduction (Azniev et al., 1988). Vegetation maintains the soil infiltration potential by preventing the sealing of the soil surface from the impact of the raindrops. Also, some of the raindrops are retained on the surface of the leaves thereby increasing the chance of their being evaporated back to the atmosphere. Transpiration by the canopy leaves bigger holes in the soil to be filled. By forming barriers along the path of the water flow over the surface, vegetation lengthens the time of concentration of runoff and reduces the peak discharge rate.

Mulch also improves the hydraulic properties of the soil. Surface mulch enhances infiltration of the soil by attracting termites whose channels provide stable micropores through which water can pass into the subsoil (Bachelier, 1978; Black, 1973).

1.6.2 Runoff Estimation

Runoff can be measured directly on the field by delineating a certain area of field and collecting and measuring the volume of water passing the downslope end of the area. Mutchler et al. (1988) gives a detailed review and description of field plots for runoff and erosion studies. The area can range from small plots (1 – 2 m²) to large catchments several square kilometers in size.

Studies of runoff in northern Nigeria generally are few. Lawes (1965) used small plots to assess runoff losses from bare and mulched plots. He obtained values as high as 45 % of annual rainfall from the bare plots. In his study over a five-year period on the ultsuls soil at Samaru, Kowal (1970) obtained a runoff value of 25.2 % on bare fallow.

There are various indirect methods of estimating runoff. Some of the widely used procedures include the rational and the curve number methods. The rational method assumes that the frequencies of rainfall and runoff are similar and it is sufficiently accurate for runoff estimation in the design of simple structures where the consequences of failure are limited. The United States Soil Conservation Service (SCS) curve number method is used for estimating runoff from total daily precipitation based on empirically derived soil parameter. The curve number indexes the absorption capacity of the soil.

A number of computer simulation models for estimating runoff exist today. The models can estimate runoff from areas ranging in size from a plot to a catchment, and for duration of rainfall ranging from event to annual total. The computer programmes use some of the above methods and/or use fundamental physical laws of science to route runoff over the surface of a field. The physically based models generally use the simplified one dimensional overland flow process in which concentrated flow is

assumed to occur in straight channels and sheet flow is expressed in terms of a discharge per unit width.

1.7. THE ROLE OF MODELLING IN HYDROLOGICAL STUDIES

Any field research programme aimed at assessing crop growth response to management factors such as runoff harvesting and water conservation must run for long periods of time to ensure that the results are representative. In situations where time and resources are limited, such long-term research studies can be conducted in relatively short time and at low costs using appropriate models. In addition, models can broaden understanding of the complex phenomena in a system.

A model relates known input with output from system of interest. Various authors (Keating et al., 1992; Carberry et al., 1992) discuss the place for models in the conduct of agricultural research under variable climates. Models that relate crop growth to climate, soil and management factors can assist in assessing strategies for enhancing crop productivity under variable climates.

To be a useful tool, a model needs to provide acceptably accurate estimates of the objective function in relation to the major factors that determine the function. Therefore, evaluation of models used for research in hydrology is important. Models used in research often emphasize detailed description of the processes and close matching of model output to field observations. Such models are usually based on fundamental physical laws of science such as the laws of conservation of mass, energy and momentum and are therefore, termed physically based models.

The advent of personal computers (PC) significantly eased the problem of computational effort required by process based models which was initially experienced. As accessibility to PC's became widespread, runoff and erosion modelling began to be developed as a tool of research and to applied hydrology. Consequently, a number of hydrologic processed-based models with spatially distributed parameters and an adequate temporal resolution emerged. However, data requirements grow with the need to define parameters at a small enough scale and

the computation time also increases with more detailed subdivision of a basin. Some examples of processed-based hydrological models include: Computer Assisted Management and Planning Systems (CAMPS), Precipitation Runoff Modelling System (Leavesley et al., 1983) and System Hydrologique European (SHE) (Abbott et al., 1986a&b). Others are KINEROS (Woolhiser et al., 1990), EUROSEM (Morgan et al., 1992), WEPP (Nearing et al., 1989), CREAMS (Knisel, 1980) and the drainage model DRAINMOD (Skaggs, 1982).

On the contrary, models used for purposes other than for research tend to emphasize ease of use, and such models are usually derived from historical observations and are termed empirical models. Examples of this type of models are the soil conservation service (SCS) curve number model (USDA, 1972), which used for estimating runoff, and the universal soil loss equation (USLE), used for estimating soil erosion by water (Wischmeier and Smith, 1978).

Due to lack of resources to deal with the huge demands to set up processed-based models, the empirical models will continue to be invaluable tools for action and regulatory programs in the developing world.

1.8. MODELLING RUNOFF IN ARID REGIONS

Arid and semi-arid regions are regions where the climate controls the hydrology (Pilgrim and Chapman, 1987). This is so because the rainfall is less and variable both in time and space. This variability, combined with sparse data, introduces a large element of uncertainty into the estimates of rainfall characteristics (Dawdy, 1991).

While the uncertainty in rainfall characteristics tends to make modelling more difficult in arid regions than in the humid regions, absence of base flow and assumption of dry antecedent conditions and empty storages after prolonged dry condition, simplifies modelling on the other hand. In addition, most actions concerning soil moisture takes place in a shallow surface layer (Dawdy, 1991) so that modelling of the soil zone is made simpler for the arid region.

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The flow diagram below (figure 1.2) shows the modelling procedure followed in the present study. Having defined the problem as that of lack of water for neem tree planting programme, models for runoff and water balance studies were reviewed and two were selected. The runoff models reviewed included the curve number (USDA, 1972), KINEROS (Woolhiser et al., 1990) and EUROSEM (Morgan et al., 1992), and the water balance models were SHE (Abbott et al., 1986a&b), SWATRE (Belmans et al., 1983) and BALANCE (Hess, 1994).

Due to their ability in representing physical processes, process-based models were preferred in the selection of the models. Process-based models take into consideration the various fundamental processes in a system and attempt to describe them adequately in mathematical forms. While the above was taken into consideration, simplicity, user friendliness and data availability played major roles in the final selection of the models.

After review of the models, it was observed that the structure of the KINEROS model is similar to that of the EUROSEM. The EUROSEM, being developed later has the added advantage of having some processes of erosion (e.g. splash, transport and deposition) represented. The above advantage of EUROSEM model together with easy accessibility to the model developers informed the decision for its selection finally.

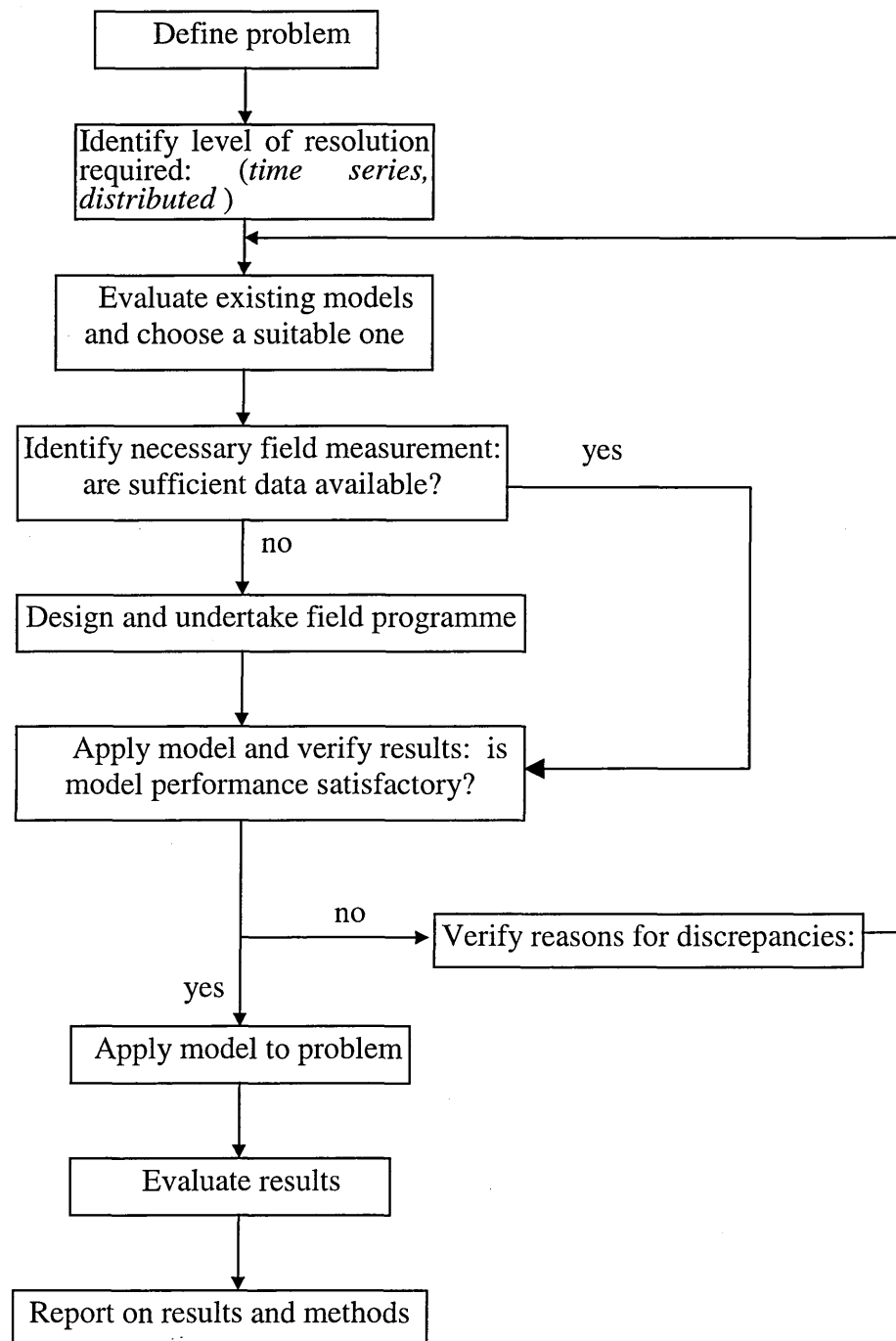


Figure 1.2: Flow chart showing the procedure followed in this study

(Modified from Watts, 1997).

The SHE model has a large computing requirements and a lot of parameterisation. It is essentially a model that broadly covers the hydrology of the temperate regions. A narrower model that can address the water balance of tropical regions was preferable. In this regard, the one-dimensional water balance model SWATRE (Belmans et al., 1983) was initially selected and tried to simulate the water balance for the northeast arid zone. Due to the extreme dry condition of the area, the unsaturated hydraulic conductivity values (calculated using the van Genuchten method) used as initial conditions were so small that the model could not converge to solutions of the equations governing water flow and the model sends error messages and crashes. The model requires estimates of many parameters in order to simulate realistic results. This proved difficult as data for this area is scanty and in some cases absent. Due to this problem, it was decided that a simpler model was going to be necessary. In view of the above, the BALANCE model (Hess, 1994) was selected to simulate the year round water balance for the area. The BALANCE model has relatively fewer and simpler parameters that could easily be determined in the field or laboratory.

1.9. AIM AND OBJECTIVES

The aim of the study is to develop a design procedure for water harvesting for the development and growth of neem tree seedlings on the degraded lands of the northeast arid zone of Nigeria.

The objectives and research strategy are

1. to develop a runoff model for water harvesting on the degraded lands of northeast arid region of Nigeria
2. to incorporate the above model into a soil water balance model, and
3. to evaluate different microcatchment sizes in terms of runoff area and basin area and recommend an optimal size

required for the survival of neem (*Azadirachta indica*) seedlings.

1.10. THESIS STRUCTURE

The thesis is reported in eight chapters, with chapter one introducing the subject and giving the general background to the methods and approach used in the study. It also includes review of the relevant literature.

The study area, identification and selection of specific sites for detailed study is presented in chapter two. This chapter also describes the general physiography of the area, the people and farming systems.

In order to carry out a hydrologic modelling study of an area, details of the soil physical and hydraulic characteristics and climate records of the area are necessary. The data collected and the methods used are reported in chapter three. Here, laboratory and field investigations regarding the soil properties and climate details that were used are presented.

Chapters four and five describe the two hydrologic models applied in the study and report results of their sensitivity analysis, calibration and validation. Surface water simulation model [EUROSEM (Morgan et al., 1998)] is described in chapter four and water balance model [BALANCE (Hess, 1994)] in chapter five.

The EUROSEM model was used in the development of an empirical rainfall-runoff model for water harvesting in northeast Nigeria and this is described in chapter six. Application and integration of the rainfall-runoff model with the BALANCE model is presented in chapter seven. Also in chapter seven, the result of a preliminary field trial of water harvesting on degraded lands is given as an annex to the chapter.

Finally, the summary of the work and its limitations, its contribution to the advancement of scientific knowledge and some recommendations for further research is presented in chapter eight.

CHAPTER TWO

THE STUDY AREA

2.1 INTRODUCTION

This chapter presents the basic geographic background to the study. As the study area lies within the sahel region, the fundamental climatic and physical characteristics of the study area are as described in chapter one. However, some of the unique physiographic features of the area are described here in terms of the location, climate, soil, agriculture and vegetation. These factors are inter-related and depend on each other.

2.2 DESCRIPTION OF THE STUDY AREA

To meet the objectives set out in chapter one, an estimated area of about 2053 km² in the NEAZDP area was selected for the study. The area lies approximately between latitudes 12° 40' N and 13° N and longitudes 11° E and 11° 21' E. Figure 2.1 shows a map of NEAZDP indicating the approximate area of study.

2.2.1 *Physiography*

River Yobe flows across the central part of the study area and runs from west to east into Lake Chad. The flow reaches its peak around September/October and is usually zero from April to June during which only swamps and pools remain to form part of the fadama. The major tributaries of the Yobe River systems are the Jama'are and the Hadejia, which rise from the Jos plateau and flow northwards towards Kano before swinging northeast to join an area of confused drainage between Hadejia and Gashua. Annual runoff in the river passing Gashua before 1972 was reported to be about $1850 \times 10^6 \text{ m}^3$ (ODA, 1972). Average peak flow of 1981 m³/s was also reported at Gashua and occurs by October. Both volume and peak flow may be lower due to damming and increased irrigation activities upstream since 1972.

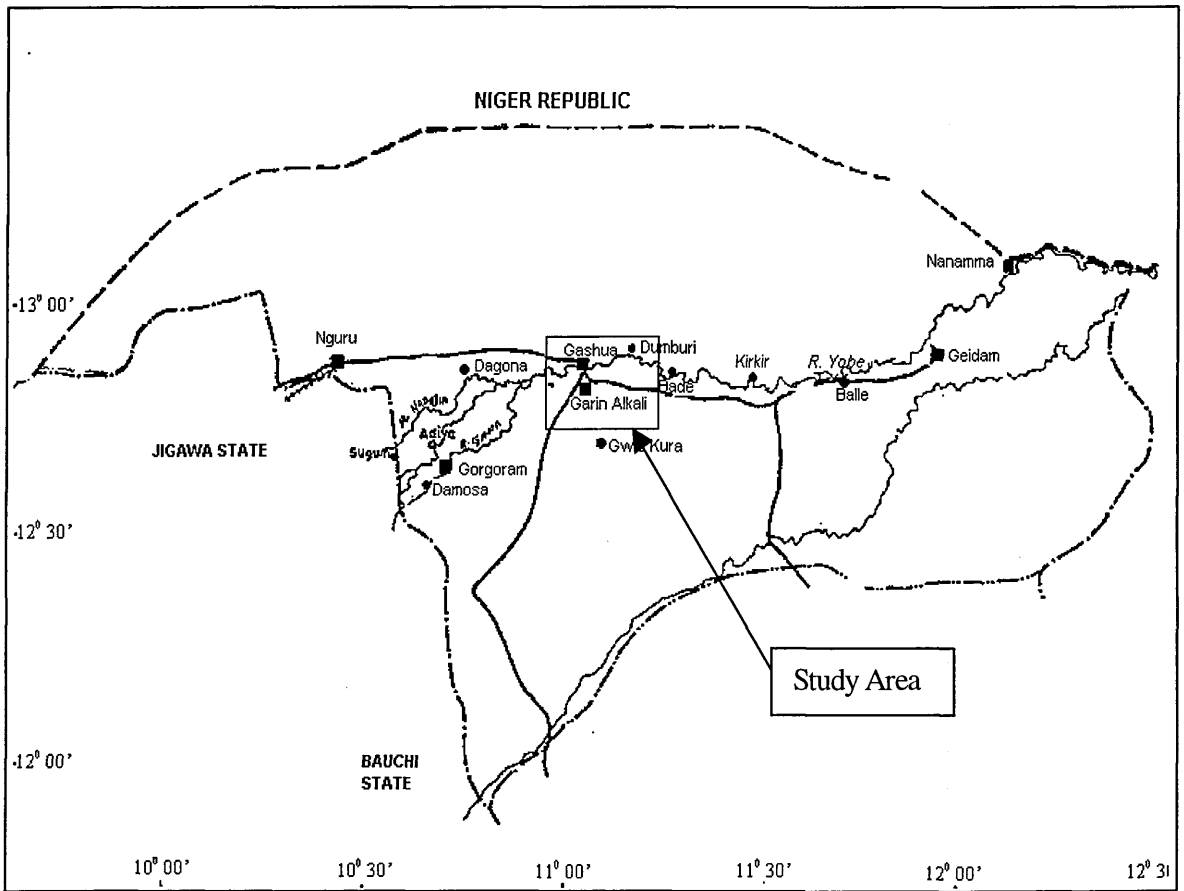


Figure 2.1: Map of the NEAZDP area showing the study area.

The study area may be divided into two major physiographic parts. One part is the floodplain or the *fadama* area. These are areas along the shores of the river. During the rainy season, they remain flooded and can cover vast areas north and south of the river and the farmers cultivate the area for rice production. After the rainy season, the waters in the floodplains gradually recede and become completely dry by the month of November and at this time the residual moisture is used for cowpea production. During the dry period, they use small-scale irrigation to produce vegetables like tomatoes, pepper and lettuce.

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The other major part of the study area is the “upland”. The relief of the upland areas can generally be described as flat or very gently undulating plains [descending from 450m in Nguru to 250m on the shores of Lake Chad (outside and east of the study area) (Abdalla, 1994)] with shallow depressions. As the study area lies in the Sahel vegetation zone, the vegetation of the upland (comprising farmlands (*tudu*), grazing areas and reserves, *fakos*, *tapkis* and built-up areas) supports vegetation of grasses and thorny bushes with scattered trees. On the *tudu*, grasses like *Cenchrus biflorus*, *Calatropis procera* and trees such as *Acacia nilotica* and *Acacia albida* can be found. Due to high moisture levels in the *tapkis*, they support a variety of vegetation including date palms (*Phoenix dactylifera*), dum palms (*Hyphaene thebaica*), *Balanite Aegyptiaca*, and shrubs like *Hyphaene Thebaica* and *Acacia senegal*.

The soils of this area has been classified as having ferroginous tropical soils (FAO, 1986). The upland’s soil surface horizons are mostly sandy in nature especially on the *tudu* and are underlain by weakly developed subsoil. The *tudu* soils are characterised by high infiltration rates and low water holding capacity, while on the contrary *fako* soils have low infiltration rates, high bulk density and high water holding capacity.

2.2.2 Climate

Rainfall

When the Inter-Tropical Convergence Zone (ITCZ) moves northwards over the Yobe basin during the months of May to August, it brings with it rain (Adams and Hollis, 1989). In the months of December and January when the ITCZ moves southwards, the tropical continental air masses bring in the cold harmattan and dust storms from the Sahara desert. This air change to dry and hot in the months of February to April. Various rainfall figures for different periods have been reported. According to Adams and Hollis (1989), based on a 10-year record, the rainfall may be under 500mm in the northern parts of the Yobe basin, while NEAZDP (1990) gave values under 350mm at Nguru and Gashua. The rainfall in this area is that of short duration

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and high intensity. Intensity of over 200mm/h in parts of northern Nigeria has been reported (Kowal and Kassam, 1976).

Temperature

The temperature in this area is generally high, and the maximum can reach around 46 °C in April/May. The coolest temperatures are in December/January with monthly means falling between 20 °C to 22 °C and this may fall to as low as 8 °C during the night (Abdalla, 1994). Due to the high temperature and low to moderate relative humidity, evaporation is high. Seasonal evapotranspiration at Nguru range between 650mm to 800mm over the period 1961 – 1990 (Hess, 1998).

2.3 IDENTIFICATION AND SELECTION OF SITES

In order to carry out experiments and detailed investigations of the area, potential sites have to be identified first. After identifying potential sites, the next task was to select representative sites. The final selection of the sites for investigation was based on a number of factors that are described under the next heading.

2.3.1 *Identification of Sites*

A reconnaissance survey was first carried out around the middle of June 1994. Visual observations were made while moving along the network of roads in the area to locate the *fako* lands.

After the preliminary survey, detailed study on the extent of these degraded lands was carried out using monochrome air photographs and mosaics (1:25000) of November 27, 1990. Original mosaic sheets covering the study area were assembled and preliminary inspection of transparencies carried out. A Stereoscope (Wild Apt 2) was used in studying the air photos and the suspected *fako* sites were marked and traced on drafting films used as overlays. These suspected sites were later checked on the field with the aid of a compass and global positioning satellite (GPS) to verify

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the sites observed on the mosaics. In the course of locating the suspected *fako* sites, informal interviews and discussions were held with the local farmers.

The areas covered by *fakos* and floodplains were estimated using the grid method. Marked floodplain and *fako* boundaries were traced on graph papers and the number of squares counted.

2.3.2 Selection of sites and field survey

Selection of sites

Among the several sites identified, three were selected for detailed study based on geographic location, accessibility and size of the sites. The sites were located at the villages of Jawa (12° 48.71'N, 11° 02.21'E) and Zurkaya (12° 49.15'N, 11° 05.52'E), and the third one about 6 km east of Gashua along Dumburi road (12° 54.31'N 11° 07.49'E).

Field topography

With the aid of level, the slopes of the sites were also estimated during the study. Heights of staff at intervals of 20 m were taken across and along the fields and the slopes were calculated in per cent.

2.4 RESULTS OF AIR-PHOTO MOSAIC AND FIELD STUDIES OF THE STUDY AREA

The aerial photos of November 1990 of the study area revealed that the floodplain covers an area of about 376 km² or 18.3 % of the study area and the remaining 81.7 % or 1667 km² comprised the upland area. The *fako* areas account for about 50 km² or 3% of the upland. These *fako areas* are denuded landscapes with scanty or no vegetation cover (plate 2.1) and are scattered within the study area. Some of the sites visited were slightly bigger in size than had been observed in the photos. This may be as a result of further degradation that has taken place over the years.

The *fako* sites vary in size from less than a hectare to around eight or more hectares. Some of the sites are not a single continuous body of *fako* but rather a cluster of adjacent *fakos* separated by small islands with some grasses of *tudu* nature. The slopes of the *fakos* are generally gentle ranging from between 0.1 to about 1 per cent. The Zurkaya *fako* site is the gentlest with 0.5 per cent around its border with a *tudu* to near flat in the middle of the field. Figure 2.2 is a schematic drawing of a typical *tudu-fako-tapki* land system. Average slope across the Dumburi site was around 1 per cent. The slopes of the three selected sites range from 0.3 to 1 per cent.

When observed visually and hand textured, the soils of *fakos* may be described as fine sand to clay loam type and are the crust forming type. The soils are very hard on the surface when dry and when broken with a hoe, a biscuit-like crumb of soil can be seen. On the *tudus*, the soils are sandier and have more vegetation. The *tapkis* were observed to be always on the downslope side of the *tudus* and *fakos*. Long grasses and trees can be seen growing in this vertisolic *tapki* soils. The soils in some of these depressions remain wet during most half of the year and some of the *tapkis* may hold enough water which the pastoralists use for drinking by their animals.



Plate 2.1: Photographs of *fako* lands at Jawa (top) and at Zurkaya (bottom).

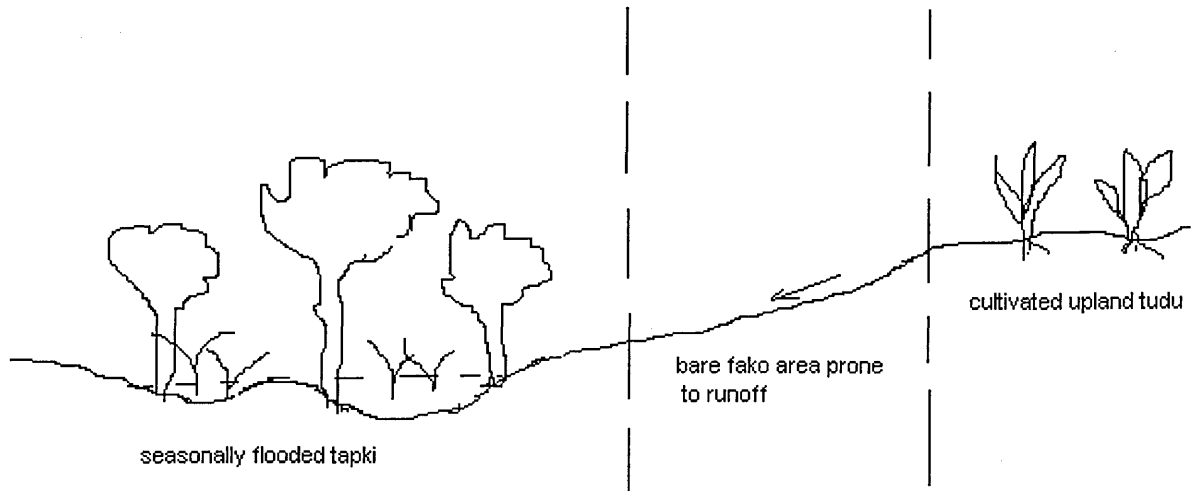


Figure 2.2: A cross section of a typical *tudu-fako-tapki* land system during rainy season.

2.5 PEOPLE AND AGRICULTURE

The inhabitants of this area are mainly Badawa, Mangawa, Kanuri, Fulani and Hausawa. They are mostly farmers who engage in small-holder subsistence farming and live in small villages. They depend on agriculture for their livelihood. The principal crops grown are millet (*Pennisetum typhoide*), sorghum (*Sorghum bicolor*) and cowpea. The Fulanis practice mixed farming. During the rainy season, the cattle graze near the villages on uncultivated lands. Some farmers collect the animal droppings for use as manure on the farms.

When asked about their perception of the *fako* lands around them, varying views amongst the farmers were noted. Some think that it does not mean anything to them

because, according to this group, they have vast areas to cultivate if they need more land. While the others think that if these lands could be put to use it will be of benefit to them as they (farmers) need to increase their production (i.e. by cultivating more lands around them without the need to travel far distances from their homes). Most of the local people welcome the idea of planting trees on these *fako* lands. The farmers recognize the importance of trees both from the view point of energy source (fuel wood) as well as checking desert encroachment (shelter belts).

Agricultural activity in the area can be divided into two; rainfed and *fadama* farming. In rainfed agriculture, the farmers cultivate the upland sandy areas for the production of crops like maize, sorghum and millet. At the beginning of the rainy season around June, most of the farmers cultivate their lands manually with hand hoes or with animal driven moldboard ploughs. Only a few of the farmers use power machines like the tractor for the cultivation. The rest of the farming activities (weeding, thinning, fertilizer application and harvesting) are carried out exclusively by manual labour.

Fadama farming is a traditional system of cultivating crops using residual soil moisture retained in the soils of seasonally flooded lands. This type of farming extends the period of cultivating the land by exploiting the residual water stored in the soil. *Fadamas* are water-logged during the wet season but retain some moisture during the early parts of the dry season. The *fadamas* are in contrast with the surrounding uplands in terms of soil moisture content during the dry season and have higher levels of soil nutrients (Kundiri, 1995). The annual inundation by the flood water results in the regular deposition of silt and other dissolved solid materials by the water. Land preparation for rice crop cultivation during the rainy season is carried out towards the end of the dry season when the soils are very dry. Ploughing of the *fadama* land is usually by tractor (Kundiri, 1995).

CHAPTER THREE

DATA COLLECTION

3.1 INTRODUCTION

The problem of marginal water supply in the northeast arid zone of Nigeria requires fundamental approaches. Effective water resource development and management could be achieved only with adequate information regarding soils, climate and weather patterns and other variables that affect the ecosystem. In view of this a number of experiments and measurements were carried out both in the laboratory as well as in the field to help understand the physical and hydraulic characteristics of the soils, the climate and weather patterns and also to build up enough information for future modelling investigations. The experiments/measurements conducted were therefore, presented under laboratory and field investigations.

3.2 LABORATORY MEASUREMENTS

3.2.1 Soil texture

Method

The soil textural class was first determined in the field by visual observation and by hand texturing. Using a hand hoe and a pair of augers, soil samples at the topsoil (0-25cm), intermediate (25-40cm) and subsurface (40-100cm) levels were taken from *tudu*, *tapki* and *fako*. About 1 kg of the soil samples was collected from each depth at all the selected sites for laboratory analysis. At the University of Maiduguri soil science laboratory, mechanical analysis was carried out on the samples. After dispersion with calgon (sodium hexametaphosphate), clay and silt were determined by the hydrometer method (Page, 1982) and sand fraction by subtraction of clay and silt from the total soil mass.

Result

Table 3.1 shows the distribution of sand, silt and clay from the laboratory analysis carried out on the samples.

Table 3.1: Textural class and per cent of sand, silt and clay of the soils at Zurkaya, Jawa and Dumburi sites.

Site	Level	% Clay	% Sand	% Silt	Tex. Class
Zurkaya fako	topsoil	25.58	40.42	34	loam
Zurkaya fako	intermediate	27.62	28.38	44	loam
Zurkaya fako	subsurface	33.60	34.40	32	clay loam
Jawa fako	topsoil	29.56	46.44	24	clay loam
Jawa fako	intermediate	33.55	32.45	34	clay loam
Jawa fako	subsurface	43.63	18.37	38	clay
Dumburi fako	topsoil	35.63	36.37	28	clay loam
Dumburi fako	subsurface	27.64	30.36	42	loam
Zurkaya tudu	topsoil	11.58	80.42	8	sandy loam
Zurkaya tudu	intermediate	13.61	76.39	10	sandy loam
Zurkaya tudu	subsurface	13.57	64.43	22	sandy loam

With the exception of the lower profile sample of Jawa, which is clayey, the soils of the *fakos* generally range between loam and clay loam with the latter dominating. The percentage of clay content generally increased from surface down the profile in almost all the sites. The surface appears to be sandier than lower down in the profile on all sites. Compared to the *tudu*, the proportion of sand on the *fakos* are far less

(about half), probably as a result of the top soil being washed away by runoff. On the other hand, *fakos* have more clay contents than the *tudus*.

3.2.2 Bulk density

Method

Four samples of undisturbed cores, two each representing the upper (0-30cm) and lower (30-60cm) levels, were taken from the *fako* and *tudu* of the selected sites. The cores used were standard brass rings 5.4cm in diameter and 3cm in height. The samples were weighed after oven drying at 105 °C for 48 hours. Dry bulk densities were calculated from the weights of the dried soil and the volume of the cylinders using equation 3.1:

$$\rho = \frac{m}{v} \quad (3.1)$$

where,

ρ = dry bulk density [g cm⁻³]

m = mass of oven dry soil [g]

v = volume of the soil sample [cm⁻³]

Result

The dry bulk density for the *fakos* range from 1.34 g cm⁻³ to 1.61 g cm⁻³ with a total average of 1.48 g cm⁻³. For the *tudus*, the range was between 1.53 g cm⁻³ to 1.7 g cm⁻³ with mean of 1.60 g cm⁻³ (table 3.2).

Table 3.2: Dry bulk densities (in g cm^{-3}) of fako and tudu soils

	<i>Fako</i>		<i>Tudu</i>	
	surface	subsurface	surface	subsurface
Dumburi	1.56	1.53	1.58	
	1.60	1.47	1.60	
Jawa	1.54	1.42	1.54	1.61
	1.43	1.61	1.70	
Zurkaya	1.37	1.56	1.53	1.59
	1.34	1.44	1.65	
Mean	1.47	1.51	1.60	1.60

The variations of the bulk density over the field may be as a result of the soil's non-homogeneity. This was observed even during sampling of the soils. On the *fakos*, some parts were very hard and dry and appeared to be more compact than others. Sampling was more difficult at such hard areas and as a result the soil had to be saturated for two days to soften it for easy sampling especially at the sub-surface levels.

3.2.3 Hydraulic Conductivity

Method

The inverse auger hole method was initially used to estimate this parameter on the field. A hole of about 8cm in diameter and one meter deep was augured. Due to the difficulty involved in auguring, three types of augers (screw, bucket and the Dutch type) were used.

However, this important soil property was also estimated in the laboratory by a different method. Some investigators compared field and laboratory determined hydraulic conductivity values and found reasonable agreement between

conductivities measured in the laboratory and in the field. Saturated hydraulic conductivity was estimated for all sites using the falling head permeameter method (Klute, 1986). Two samples from each site were collected for laboratory test. In order to obtain undisturbed samples easily, the soil was first brought to field capacity by flooding and then allowed to drain for two days. Undisturbed samples were collected in 150mm-diameter rings for the falling head test. Permeameter cell was set in a bath of water at room temperature. After two days of saturation, the cell was fitted to a falling head permeameter. Water was flushed through the samples to ensure air bubbles were removed before measurements. Different head levels were applied and water levels allowed to drop to about 10cm. Calculations were carried based on the direct application of Darcy's equation (equation 3.2):

$$K_s = \left[\frac{aL}{At} \right] \log_e \left(\frac{H_1}{H_2} \right) \quad (3.2)$$

where,

K_s = saturated hydraulic conductivity	(mm h ⁻¹)
a = diameter of pipe above soil column	(mm)
L = height of soil column	(mm)
A = cross-sectional area of soil column	(mm)
H_1 = initial water level in standpipe	(mm)
H_2 = water level in standpipe after time t	(mm)
t = time taken for water to drop from H_1 to H_2	(h)

Result

The saturated hydraulic conductivity obtained with the inverse auger-hole method was low. The values ranged between 1 mm h⁻¹ and 3 mm h⁻¹. With the permeameter method, the values were slightly higher. K_s values of between 2 mm h⁻¹ and 6 mm h⁻¹ were obtained (see table 3.3).

Table 3.3: Saturated hydraulic conductivity values(in mm h⁻¹) for Jawa, Zurkaya and Dumburi sites with a falling head permeameter and inverse-auger hole methods.

Site	Permeameter method		Inverse-auger hole method
	Range	Mean	
Jawa	3 - 5	4	2
Zurkaya	2 -3	2.5	2
Dumburi	4 - 6	5	3
Mean	4*		2.3

* n=12

Although high bulk density values were recorded on the *fakos*, the inverse auger-hole method may have under-estimated the K_s value. The under-estimation may be as a result of the way the holes were made. Due to the hard nature of the *fako* soils that necessitated the use of different types of augers, there was plastering and sealing effect on the walls of the holes by the augers. This might have altered the flow of water across the walls into the profile and consequently gave low K_s values.

Considering the high variability of saturated hydraulic conductivity, the values of K_s obtained revealed that the hydraulic characteristics of *fako* soils is less variable, though large number of samples could not be collected due to logistics.

3.2.4 Water Retention

One of the main parameters affecting one-dimensional vertical flow of water in the unsaturated zone is the soil water retention characteristic. The soil water-retention curve defines the relationship between soil water content and soil water tension. This property of the soil was investigated in the laboratory on undisturbed soil cores obtained from the field.

Twelve undisturbed samples were collected in brass rings (two at 0 - 25cm depth and two at 25 – 40cm depths for Jawa, Zurkaya and Dumburi sites) and then saturated in

a tray by capilarity with constant water depth of 10cm for six weeks. After weighing the saturated samples, they were transferred to a sand table where they were covered with black polyethylene sheet at the upper faces and with a piece of nylon voile at the lower faces. The samples were then brought to equilibrium at a series of increasing suctions of 2, 4, 6, 8 and 10 kPa using sand table. They were then resaturated for another desorption stage using the pressure membrane apparatus (Klute, 1986). Here, the sequential pressures applied were 100, 200, 400, 800 and 1500 kPa. At the end of this desorption, the samples were removed, weighed and oven dried at 100 °C for 48 hours. The equilibrium weights were used to calculate moisture content for any given suction after the samples were oven dried.

Result

Moisture contents obtained at various suctions on the samples were fitted to Van Genuchten (1980) model to obtain the water release curves (figure 3.1) and the Van Genuchten parameters. As can be seen from the *fako* curves, the soil water content decreases from 0.4 at 1 kPa to about 0.2 at 1500 kPa. For the *tudus*, the soil water content remains fairly constant at around 0.3 from 1 kPa to about 25 kPa tension and then decreases rapidly to less than 0.1 at 100 kPa. The soils of the *fakos* have higher water holding capacity compared to that of the *tudus*. Values ranging from 0.18 to 0.21 volume water fraction were obtained. However, as this observation was carried out on the drying cycle, the effect of hysteresis should be considered for quantitative hydrological studies.

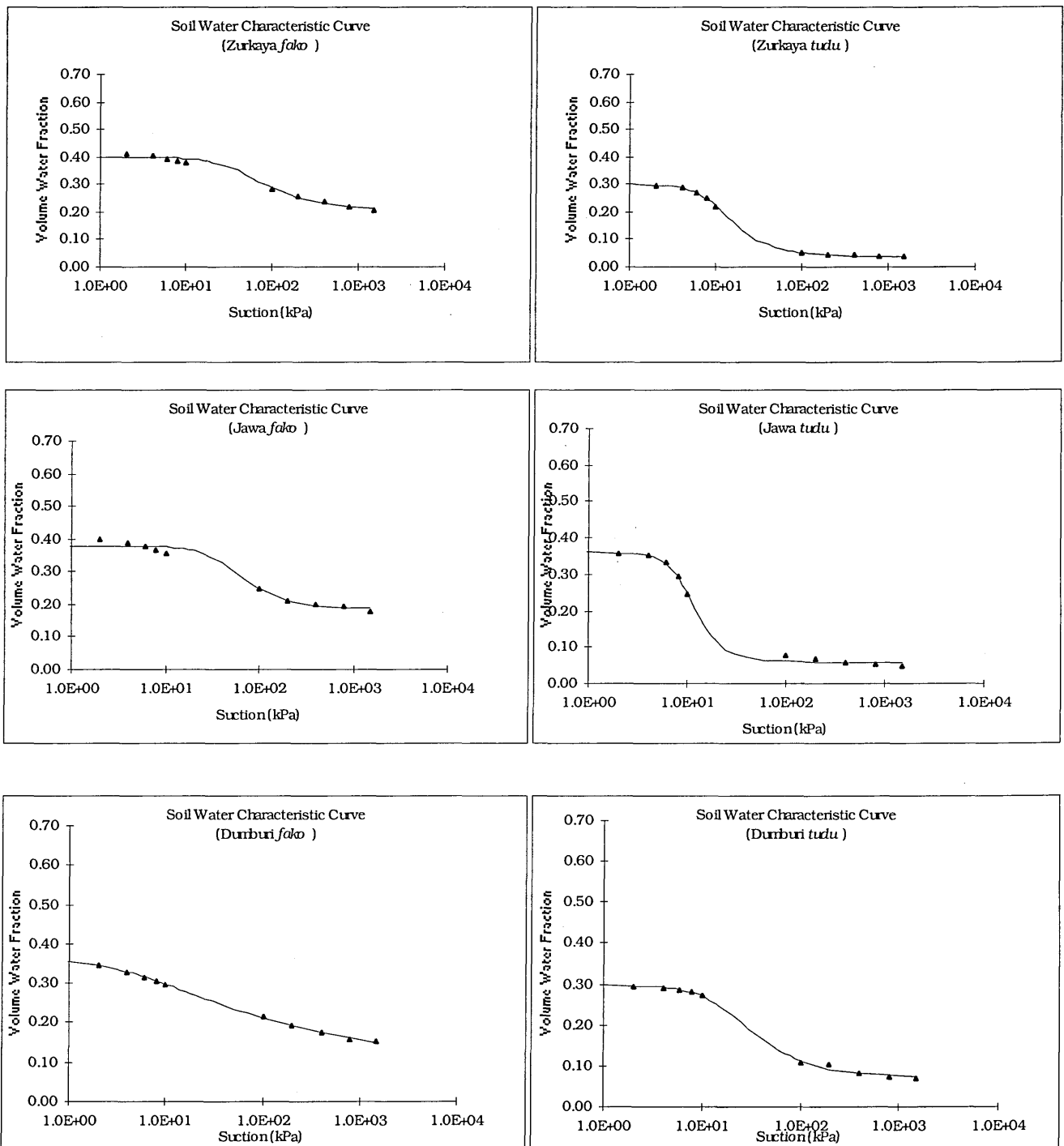


Figure 3.1: Water release curves of *fako* and *tudu* for Zurkaya, Jawa and Dumburi areas.

3.2.5 Rainfall simulation

Rainfall simulation is the controlled production and application of water drops to plots using nozzles, yarns, small tubes and other drop formers. Most rainfall characteristics can be simulated to some certain degree with rainfall simulators, but usually they cannot exactly replicate natural rainfall (Bubenzer, 1980; Meyer, 1958).

The first pressurised rainfall simulators were used for erosion research in the 1930s (USDA 1979). Young and Burwell (1972) showed that the Meyer-McCune (1958) rainfall simulator generates erosion and runoff similar to that under natural rainstorms. This artificial way of reproducing rain has gained acceptance and therefore has been applied to several areas of research in runoff (Meyer-McCune, 1958), soil erosion (Meyer, 1979) and infiltration studies. Rainfall simulators were used in the development of the USLE soil erodibility nomograph and cover management factor values for conservation tillage (Wischmeier and Smith, 1958). Some of the advantages of simulated rain are that it is controllable in both time and space and can be repeated several times in a very short time period. However, the quick changes in intensity of natural rainstorm which cannot be simulated, coupled with the fact that large rainfall simulators are very cumbersome and require a lot of water are some of its disadvantages.

Rainfall simulators can be classified as being either non-pressurised or pressurised. In non-pressurised simulators, raindrops are allowed to fall under gravity and do not require pumps to convey water to the drop formers. Drop formers have small internal diameters below a tank of water with a constant head. Hypodermic needles and capillary glass or brass tubes have been used as drop formers. Meyer (1958) and Hudson (1964) provide detailed information on drop formers and drop formation.

Pressurised rainfall simulators involve the use of pumps to spray drops out of a nozzle under pressure. An initial velocity is imparted to the drops so that they reach their terminal velocities at less fall height than for drops falling from the skies. Hopefully, terminal velocity is achieved before the drops make contact with the

target surface. Terminal velocity varies with drop size. Larger drops have higher terminal velocities and hence higher kinetic energies (Laws, 1941).

Rainfall simulation in the laboratory

Before carrying out simulations on the field, laboratory investigations were conducted at Silsoe to evaluate nozzle characteristics in terms of the range of intensity and drop size distributions they can produce.

Method

The nozzles were fixed at a height of 2.25m above an area of 1.33m by 1.33m. Water was supplied from a pump driven by an electric motor. A valve controlled intensity of water produced by a nozzle over the area. The higher the pressure, the more intense the rain produced. The pressure in the system was monitored by a pressure gauge. Five catch cans each measuring 12cm in diameter and 20cm deep were placed diagonally across the area to collect the rain over a period of time. Average intensity over the area was calculated from the amount of water collected in the can over the time.

Drop size distributions produced by the nozzles were investigated using the flour pellet method (Hudson, 1964). After taking the measurements for the intensity, drops were caught in fresh flour and the pellets formed were dried in an oven at 105 °C for 12 hours. After drying, the pellets were separated according to size using different grades of sieves. The number of pellets in each grade of sieve were counted and weighed.

Result

The results of intensity and drop size distribution over the area obtained with different types of nozzles and at various pressures are presented in table 3.4 and table 3.5 respectively. Depending on the type of nozzle and the pressure setting, total simulation times varied between 10 and 30 minutes each. Periods of intensity measurements varied between 5 minutes and 20 minutes (table 3.4).

Table 3.4: Rainfall intensities obtained with different types of nozzles at various pressures.

Nozzle	Pressure (kPa)	Period of measurement (min)	Average intensity* (mm h ⁻¹)	Coefficient of variation (%)
Metallic type (old)	117	10	51	11
	103	20	50	11
Metallic type (new)	69	10	29	7
	103	10	45	7
	117	10	49	9
	138	10	62	10
	172	10	77	10
Plastic type	138	5	552	14
	117	5	556	27

* Three replicates each

The plastic type nozzle produced the highest intensity. The average intensity recorded over the area at 138 kPa pressure was 552 mm h⁻¹ with a coefficient of variation of 14%. The coefficient of variation increases with decrease in the system pressure with this nozzle. The nozzle also produced bigger drop sizes. The median drop diameter was 1.86mm at 138 kPa(table 3.5).

Table 3.5: Median drop diameter(D_{50}) obtained at representative (low, medium and high) intensities.

	Nozzle specification	Pressure (kPa)	Average intensity (mm/h)	D_{50} (mm)
low intensity (metallic)	Lechler type- (no 402686)	69	29	0.96
medium intensity (metallic)	Lechler type- 30 aperture (no 402846)	138	62	1.16
very high intensity(plastic)	Delavan type- 1/2 BQM 32 aperture	138	552	1.86

The metallic nozzles can produce low to medium intensities at pressures of less than 180 kPa. Compared to the plastic type nozzle, they can produce better results in terms of uniformity of distribution of intensity and drop size over the area. They give lower coefficient of variation under the same pressure. The median drop diameters of the two metallic nozzles were 0.96 mm at 69 kPa and 1.16 mm at 138 kPa respectively.

However, excessive pressure is required in order to produce high intensities with the metallic nozzles. Therefore, for intensities in excess of 100 mm h^{-1} , the plastic nozzle is suitable.

3.3 FIELD MEASUREMENTS

The parameters and variables estimated on the field were runoff, soil evaporation, soil moisture, infiltration rate and climate data, and each is discussed in turn below.

3.3.1 Runoff

Runoff on the soil surface can be generated as a result of natural rainfall or from artificial rain produced by rainfall simulation. In this study runoff was generated artificially on the field using rainfall simulator.

Rainfall simulation in the field

There were five major components of the rainfall simulator used in the field study:

1. Water is the most important input in any type of rainfall simulator. The supply of water may constitute a major problem in terms of quantity and quality. The former can be a serious constraint especially in remote areas, and the problem of contaminants may cause blockage of the drop forming devices. In this study, supply of water was the problem. Water was carried in 200 litre drums in Land Rover from the source (NEAZDP headquarters) to the sites. Jawa, Zurkaya and Dumburi sites are about 3 km, 6 km and 12 km from the source.
2. Pressurised rainfall simulators require pumps to supply water under pressure to the simulator head (usually a nozzle or set of nozzles). Pumps require a source of power. The simulator used in this study consisted of a 2.8 hp petrol engine with a maximum pumping capacity of 530 l/min. The speed of the pump can be increased or reduced by a throttle valve. The inlet and outlet delivery ends of the pump were 3-inch in diameter each and the maximum head of the pump was 35m. An adapter was constructed to reduce the outlet diameter from 3 inch to 1 inch. A pressure gauge was fixed on one side of the nozzle head for monitoring the pressure of the water being delivered.
3. The pipe work supplying water can be rigid or flexible. Rigid pipes can be difficult to handle especially when a lot of movement from one place to another is involved, which was the case in this study. Therefore, flexible hoses of 3 inch diameter were used. Caution was however, exercised as flexible hoses can coil easily. If coiled, they can lead to friction and build up of pressure, which may result to bursts or even breakdown of the pump.

The rainfall simulator head must be supported on a frame. The Land Rover roof rack was used as a means of cantilevering the nozzle over the plot using aluminium (neutron probe access) tubes as supports (see plate 3.1). The height of nozzle over the soil surface obtained with this arrangement was about 2.5.

4. Nozzles have tiny holes through which the water is passed to form water droplets. There are various types of nozzles that give different drop sizes and drop velocities and consequently different intensities. Two types (metallic and plastic types described earlier) that give good distribution of low, medium and high intensities were used.

The border of the plots on which simulations were conducted was made from iron sheet 3mm thick and 5cm high. The four sides (2m long \times 1.5m wide) were joined together by electric arc welding. A 10 cm opening was left on one of the shorter sides to serve as outlet. The pre-made border was carried from the workshop to the required position on the field where it was pressed and hit gently to about 2cm into the soil. A ditch, 30cm in diameter and 30cm deep was made at the downslope end of each plot for collecting runoff.

Simulations were conducted first away from the plots for between 5 to 10 minutes where intensities were measured with standard raingauge before being moved on to the plots. Depending on the intensities, simulation times on the plots ranged between 10 to 40 minutes. Runoff was collected in a 5-litre container intermittently at the lower end of the plots. Using a measuring cylinder, the collected runoff was measured and the runoff rate calculated. Soil samples were collected before the start of each simulation for gravimetric moisture content determination.



Plates 3.1: Rainfall simulator set-up (top) and (below), a plot soon after simulation.

Result

The runoff flow rates measured under a range of intensities over the Jawa, Zurkaya and Dumburi plot-sites are presented in appendix A. A pair, representing high and low intensities from Zurkaya site is presented in table 3.6 as an example.

The runoff flow rates generated on the plots were plotted against corresponding times to obtain hydrographs. The best description of the hydrograph was given by a logarithmic function. Runoff volumes were computed from the hydrographs by integration (equation 3.3) and the result is presented in table 3.7.

$$V = \int_{\alpha}^{\beta} [m \ln(x) + c] dx \quad (3.3)$$

where

α & β are times after start of rain during which measurements were taken.

m & c are the slope and intercept of the graph obtained respectively.

Table 3.6: Some rainfall simulation data for Zurkaya site.

Average Intensity = 127 mm h ⁻¹				
Initial moisture	>>	0.026		
Rain started at	>>	9:37 am		
TIME	(h:min:s)	volume collected (l)	Duration (min)	Runoff rate (lit/sec)
from	to			
9:41:15	9:41:30	0.96	0.25	0.0640
9:42:45	9:43:00	1.07	0.25	0.0713
9:45:15	9:45:30	1.06	0.25	0.0707
9:48:15	9:48:30	1.13	0.25	0.0753
9:51:00	9:51:15	1.2	0.25	0.0800
9:53:30	9:53:45	1.12	0.25	0.0748

Average Intensity = 38 mm h ⁻¹				
Initial moisture	>>	0.143		
Rain started at	>>	9:45 am		
TIME	(h:min:s)	volume collected (l)	Duration (min)	Runoff rate (lit/sec)
from	to			
9:57:00	9:58:00	0.35	1.00	0.0058
9:59:30	10:00:30	0.55	1.00	0.0093
10:01:45	10:02:30	0.72	0.75	0.0160
10:03:10	10:04:10	0.95	1.00	0.0158
10:05:10	10:06:00	0.95	0.83	0.0191
10:07:30	10:08:30	1.05	1.00	0.0175
10:09:30	10:10:30	1.05	1.00	0.0175
10:12:35	10:13:35	0.92	1.00	0.0153

Table 3.7: Runoff volumes from various rainfall intensities at the three sites.

Site	Rainfall intensity (mm h ⁻¹)	Runoff volume over time interval β - α (litres)	α (min)	β (min)	Average discharge (mm h ⁻¹)
JAWA	36	1.4	18	32	2.0
	60	13.6	2	15	20.9
	60	14.6	3	15	24.4
	65	19.4	13	26	29.8
	145	44.0	2	13	80.4
	169	62.0	2	18	76.9
	25	0.5	8	22	0.7
	32	4.0	11	25	5.7
	45	12.9	16	30	18.4
	54	17.5	4	15	31.9
	156	30.5	4	10	101.6
ZURKAYA	127	58.0	4	17	89.2
	50	10.9	6	17	19.8
	37.5	11.1	13	29	13.9
	41	6.8	11	21	13.6
	135	46.2	0	11	84.0
	32	12.6	6	17	22.9
	142	29.2	2	10	73.0
	156	38.4	3	10	109.7
	162	12.3	3	8	49.2
	50	12.4	0	13	19.1
DUMBURI	58	7.6	3	10	21.7
	41	17.3	3	16	26.1
	120	25.4	5	12	72.6
	65	13.2	3	13	26.4
	48	20.8	14	31	24.5
	32	13.1	4	20	16.4
	52.5	9.8	21	34	15.1
	72	16.7	2	14	27.8
	145	57.2	2	12	114.4

The average discharge generated over the plots ranged from 0.2 mm h^{-1} to 114.4 mm h^{-1} . These values were obtained at rainfall intensities of 25 mm h^{-1} and 145 mm h^{-1} respectively. Although some of the rains were of higher intensities, (e.g. 169 mm h^{-1}) they did not generate correspondingly higher discharges. This was because of the initial condition of the soil and the period of taking the measurements. At the beginning of simulations on each site (the first simulations), the soils were very dry and therefore required more water to saturate the soil and fill up any available micropores. Subsequent simulations had wetter initial conditions and smoother surfaces (sealing effect as a result of previous simulations) that easily initiated runoff. Also, due to the intermittent way of measurements, some runoff measurements were taken before reaching the time of concentration. Therefore, these two situations and some possible errors in measuring the intensities would have been responsible for the lower discharge values resulting from higher intensities.

3.3.2 Soil evaporation

This experiment was carried out with two objectives. The first was to gather moisture content data for the calibration and validation of a water balance model, BALANCE (Hess, 1994) and secondly, to test the effect of covering the soil surfaces with different polyethylene materials on soil evaporation.

In the experimental set-up, three treatments were tested. They included soil covered with solid polythene, soil covered with perforated polythene and soil with no cover. The treatments were replicated three times. Therefore, nine $2\text{m} \times 1.5\text{m}$ plots were constructed at each site. The borders of the plots were constructed with the surrounding soil to a height of about 20 cm (see plate 3.2). The surfaces of the plots were tilled with hand hoe to encourage infiltration and were then flooded with water for 3 days. Soon after the water dried out on the last day of the flooding, the covers were put on two of the treatments and then buried lightly with soil. The third treatment was left without cover. Moisture content on each plot was monitored at 5 cm interval down to the wetting front at about 2-3 weeks interval. A graduated iron

pipe was used in taking the samples from the soil profile. The pipe was driven manually to the required depth. Water contents of the samples were determined gravimetrically. Monitoring continued up to a period of about 13 weeks.

Result of the Experiment

The complete moisture content at various depths for each treatment at the different dates is presented in appendix B. As expected, the result of the experiment showed only minor difference in the moisture contents between replicates and between treatments on the first day of the experimental set-up. The minor differences may be due to slight variations in the soil structure caused by the tillage and/or in quantity of water applied. Moisture content on this day was high at the surface in all cases, and was consistently dry below 20cm.

Figure 3.2 summarises graphically the result of the Zurkaya site. Three weeks after set-up (figure 3.2b), a big difference can be seen between all the treatments. Moisture content was highest in the solid cover treatment and below permanent wilting point in the control plot. The difference was highest at the upper parts of the soil and tended to narrow with depth. Difference between the solid and perforated was much only at the top 10cm of the soil.

Three months later (figure 3.2c), the solid treatment clearly had more moisture content up to the depth of 30 cm. The difference between the treatments was however, not much at 30cm depth. This might be as a result of less water reaching that depth in all the treatments.



Plate 3.2: Soil evaporation plots at Zurkaya site.

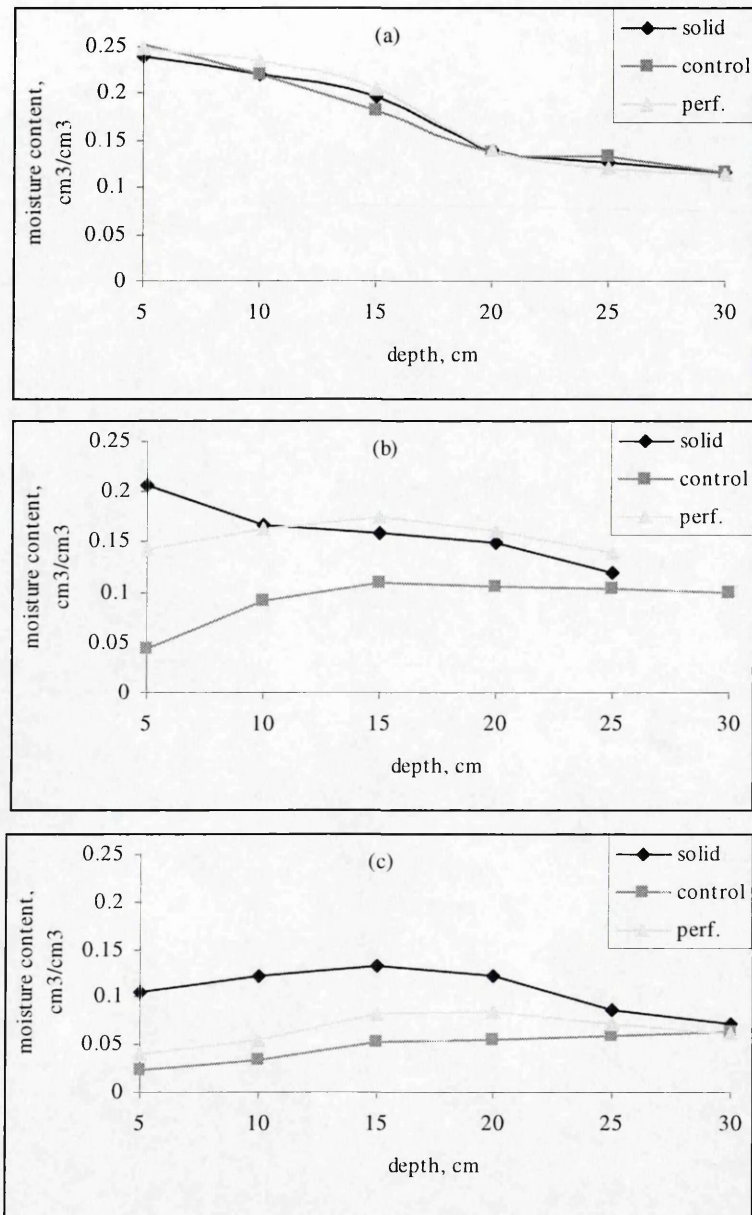


Figure 3.2: Average soil moisture with three cover treatments at different times after set-up at Zurkaya site. Where (a) is on the first day, (b) 3 weeks after set-up and (c) 13 weeks after set-up.

In conclusion, the solid cover retained the most moisture compared to the others. This was expected because it has the maximum cover and therefore restricts soil evaporation due to net radiation and air movement over the soil surface. While it desirably reduces soil evaporation, the solid polyethylene may not be suitable in a situation where infiltration of rain and free air circulation is sought. The perforated cover treatment shows that it can also reduce soil evaporation significantly. The perforated polyethylene provides a compromising effect by reducing soil evaporation on the one hand, and allowing unrestricted infiltration of rain and free exchange of gases between the soil and atmosphere on the other.

3.3.3 Soil moisture

The objective of this part of the study was to characterise the natural soil water regimes on the *tudu*, *fako* and in the *tapki*. Access tubes were installed on the three land systems and neutron technique was used in determining the soil water. Due to ponding in the *tapki* at the time of installation, the tube was installed at the edge of the *tapki*. Installation of the access tube on the *fako* was more difficult compared to those on *tudu* and *tapki*. This was because of its dry and hard nature. Neutron readings were taken at 10cm intervals from 20cm down to 160cm depth at weekly time intervals.

Result of Soil Water Monitoring

Figure 3.3 shows the soil moisture profile on the *tudu*, *fako* and in *tapki* at Zurkaya site. There was more moisture in the upper 100cm of the profile of the *tapki* compared to the *tudu* and *fako*.

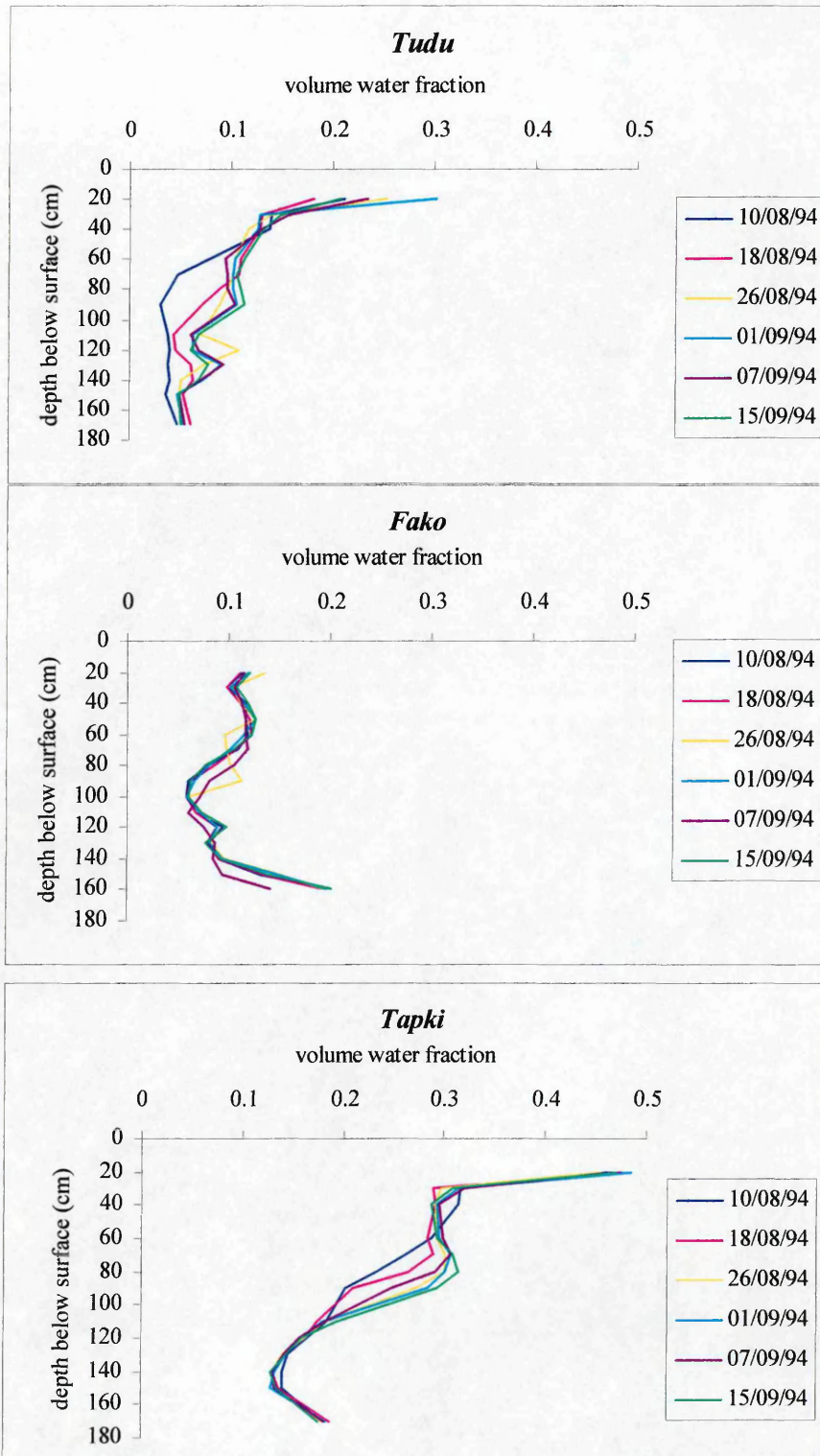


Figure 3.3: Soil water for *tudu*, *fako* and *tapki* at Zurkaya on different dates.

Volume water fraction of about 0.5 at around the surface of the *tapki* was recorded on almost all dates during the period of measurement. The high value was as a result of ponding on the surface. The low elevation of the *tapki* makes it a natural storage point for all the runoff flowing down from the *tudu* and *fako*. However, at depths of 60-110cm, there was gradual increase in the moisture content with time. This may be due to the slow and steady infiltration of the ponded water at the surface which eventually is stored in the profile. The *tapki* soil being clayey, allows very slow seepage of water through it.

On the *tudu*, the moisture content at the upper part of the soil profile was much less than that of *tapki* but higher than that of the *fako*. Due to its sandy nature, much of the rains on the *tudu* infiltrate the profile but substantial part is lost to deep drainage.

Except at depths below 150cm, the soil moisture content of the *fako* was virtually constant. Volume water fraction for this depth was below 0.1 on all dates. The *fako* soils, with high bulk density and low infiltration rate, restricts water entry into the soil profile and substantial part of the rain runs off with only a small per cent of it finding its way through the top few centimetres of the soil profile.

3.3.4 Infiltration Rate

After reaching the soil surface, raindrops ultimately infiltrate the soil, evaporate or become a part of overland flow and eventually run off. The rate at which water can enter the soil depends on many factors, among which may be soil texture, canopy cover, soil surface crusting, rainfall energy, slope, bulk density and moisture content of the soil. Liquid water movement in unsaturated soils takes place through soil moisture films or in small pores through the combined action of gravitational and capillary forces. Therefore, any factor in the soil system that affects the magnitude of the capillary conductivity and the potential gradient will likewise affect the infiltration capacity.

Research into the process of partitioning rainfall at the soil surface has led to the development of several infiltration models (e.g. Green & Ampt, 1911; Kostiakov,

1932; Horton, 1940; Philip, 1957 a,b). Many researchers (e.g. Amerman, 1983; Talsma & Hallam, 1980) use the final constant rate of infiltration as a single figure with which to compare soils and assume that soils with smaller values tend to pond more quickly during rainfall. Kumke and Mullins (1997) disagree with this assumption because according to them, time to ponding also depends on the sorptivity, which is a function of the soil matrix potential before infiltration (Reynolds and Elrick, 1986).

Infiltration rate of the study area soil was estimated on the field by flooding technique using the double ring infiltrometer. The double ring infiltrometer has been found to be a rapid and simple field technique (Talsma, 1969). However, some of its disadvantages are overestimation of the sorptivity due to flow through micropores (Clothier and White, 1981) and divergence. Measurements of the rate of fall of water in the inner ring were conducted on *fako* and *tudu* areas. The results of the cumulative infiltration measurements were fitted to Philips (1957) equation (3.4).

$$F = S t^{0.5} + K t \quad (3.4)$$

where, F = cumulative infiltration	(mm)
t = time	(h)
S = sorptivity	(mm h ^{-0.5})
K = constant	(mm h ⁻¹)

The constant K , under steady state conditions may be equated to an effective hydraulic conductivity in the wetted transmission zone (Hillel, 1982)

The values of S and K for each measurement were estimated iteratively using Excel Microsoft Solver. Differentiating (3.4) with respect to time gives the infiltration rate I ,

$$I = 0.5 S t^{-0.5} + K \quad (3.5)$$

Figure 3.4 shows the infiltration rates for *fako* and *tudu* at Jawa, Zurkaya and Dumburi sites as calculated by equation 3.3. In agreement with the classical approach used by Horton (1940), the rate of drop was fast initially, and decayed from some initial rate to a final constant rate as time approaches infinity.

From equation (3.3), as time becomes large, I tend to the eventual value of intercept K , which is the final infiltration. The K values for the *fakos* ranged between 2.4 mm h⁻¹ and 6 mm h⁻¹, and for the *tudus* the range was from 12 mm h⁻¹ to 45.6 mm h⁻¹. From the field measurements, I values of between 18 mm h⁻¹ and 72 mm h⁻¹, and between 6 mm h⁻¹ and 36 mm h⁻¹ at the initial and final stages respectively, were recorded on the *fakos*, while that for the *tudus* were from 120 mm h⁻¹ to 450 mm h⁻¹ and 48 mm h⁻¹ to 90 mm h⁻¹ for the initial and final rates. The infiltration rate for the *tudu* was between four and eight times that of the *fakos*. The nature of the soils is responsible for the difference in the infiltration rates. *Tudu*, being sandier, has larger pores through which water can move down the profile easily and quickly. Also, the layer of crust obtainable on the surface of *fakos* is almost absent on the *tudus*. The crust restricts water crossing the soil surface and acts as a hydraulic barrier that inhibits infiltration on the *fakos*. In some cases of the measurements on the *fakos*, the usual sharp initial drops were not noticed. This might be as a result of the presence of crusts to a large extent and the initial moisture of soil to small extent. The wetter the soil is initially, the lower the initial infiltration rate will be owing to smaller suction gradient, and the quicker the attainment of the final constant rate.

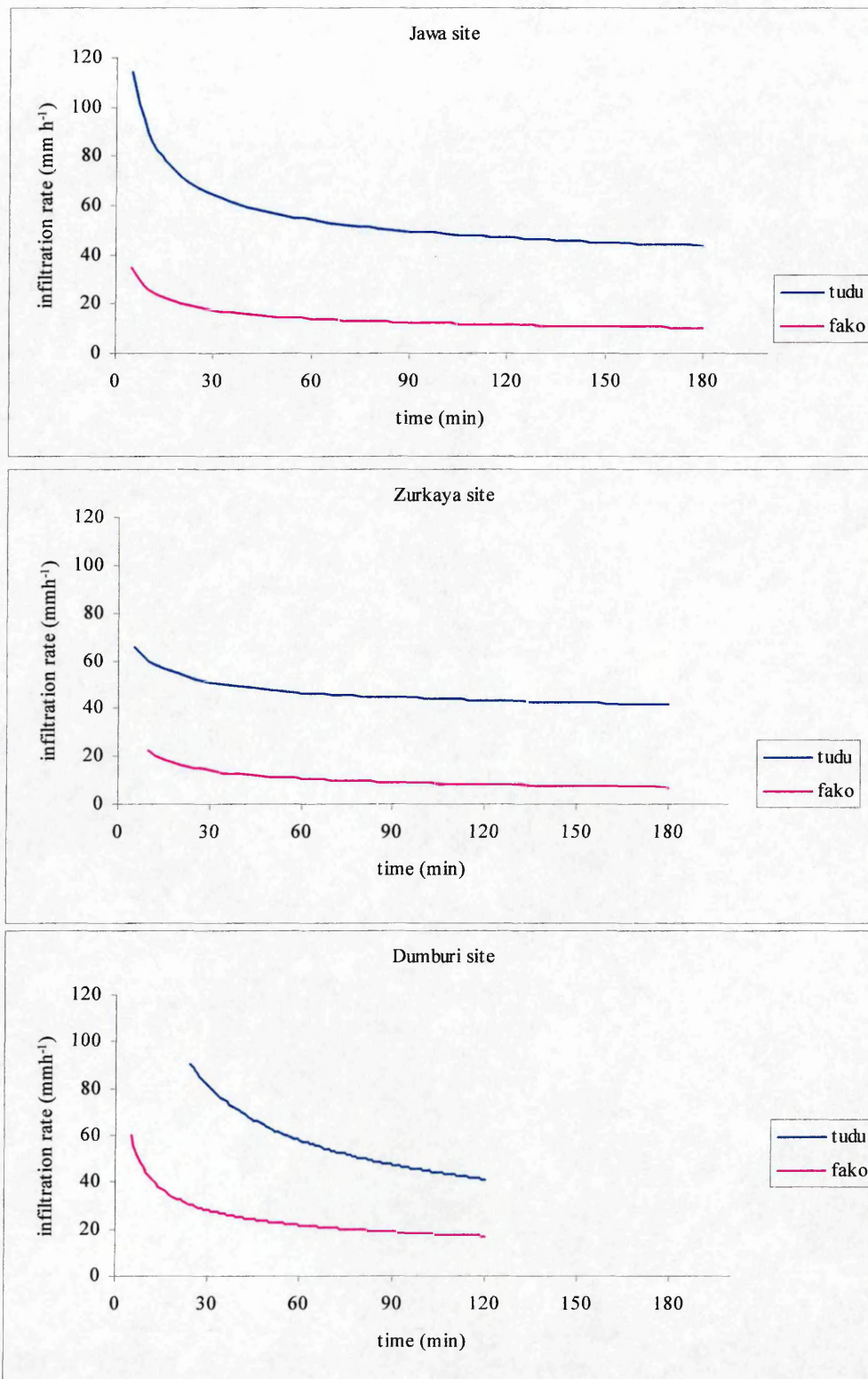


Figure 3.4: Infiltration rates on *tudu* and *fako* at Jawa, Zurkaya and Dumburi sites.

3.3.5 Climate Data

Automatic raingauges were installed at Jawa, Garin Alkali and Zurkaya to monitor and collect high resolution rainfall data. The rainfall data from the three stations were recorded with SKYE raingauge having a resolution of 30 seconds. The data logger of the raingauge was programmed to record the number of tips only. Offloading of the data was done fortnightly and stored for subsequent analyses. The data for these stations were collected between June and mid September of 1994. Also, daily rainfall data for previous years were collected from Nguru, a station within the NEAZDP area. Other climate data (evaporation, temperature, relative humidity and wind speed) were collected from the NEAZDP headquarters.

Rainfall data for the period 1992 to 1994 for four other stations (Kaska, Futchimiram, and Dagaceri in the NEAZDP area and Tumbau outside NEAZDP area) were obtained. DIDCOT type raingauge was used in recording the data for the four stations. The resolution of the DIDCOT was 1 minute. The complete data collected by these raingauges is given in appendix F

In addition to the high resolution data, daily rainfall records from manual raingauge at Garin Alkali and Gashua were collected.

Result

At Zurkaya and Jawa stations, the total amount of rainfall recorded during the 1994 rainy season were 478.4 mm and 576.8 mm respectively. During the same period of time rainfall amount at G/Alkali was 503.4 cm, which is close to the average (527.6 mm) of Zurkaya and Jawa. Due to malfunction of some of the DIDCOT raingauges, some data for the 1992-94 period could not be obtained. Altogether, high resolution data for 13 site-year period was obtained. For the daily rainfall data, 30-year record (1961-1990) was collected for Nguru station.

3.4 CHAPTER SUMMARY

Some water balance components and soil physical and hydraulic parameters were estimated in the laboratory and in the field. Runoff was estimated on the *fako* areas of Zurkaya, Jawa and Dumburi sites using artificial rainfall. Rainfall simulator was constructed and different intensities were simulated to obtain a range of runoff flow rates. The intensities simulated ranged from 25 mm h⁻¹ to 169 mm h⁻¹, which is a good representation of the intensities expected in the area. Average runoff discharges resulting from these intensities ranged from 0.7 mm h⁻¹ to 114.4 mm h⁻¹.

The soil physical and hydraulic characteristics investigated were texture, bulk density, hydraulic conductivity, infiltration rate and water retention. For *tudu* and *tapki*, the soils were found to be mostly sandy and clayey respectively. The texture of the *fako* soils was predominantly clay loam with a high water holding capacity. Volume water fraction of over 0.2 was recorded. The bulk density ranged from 1.34 g cm⁻³ to 1.61 g cm⁻³. Saturated hydraulic conductivity varied between 2 mm h⁻¹ and 6 mm h⁻¹.

Experiment was conducted to determine the effect of cover on soil evaporation and temporal variation of soil moisture content on the *fako* areas. It was concluded that perforated cover on the soil surface could reduce soil evaporation and at the same time allow infiltration of rain. The moisture content data collected from the experiment also formed a database for subsequent modelling studies.

Climate data for the area were gathered. High resolution rainfall data for 13 site-years from seven stations within the NEAZDP area were collected using automatic raingauges. Daily rainfall record for 30 years from Nguru meteorological station was collected. Other climate data (temperature, humidity, sunshine and wind run) for Garin Alkali were also collected.

CHAPTER FOUR

THE EUROSEM MODEL

4.1 INTRODUCTION

The European Soil Erosion Model (EUROSEM) is a physically based, distributed erosion model developed by Morgan et al. (1998). Modelling soil erosion by water requires adequate and detailed procedures of modelling the generation of runoff and its routing down a hillslope. EUROSEM simulates runoff on a surface using the runoff generator of the KINEROS model (Woolhiser, 1990) to which it is linked. The model can simulate runoff and erosion from single plane or element, multiple planes or elements and multiple planes and channels. The time interval of model operation may vary from a few minutes to several hours, depending on the storm duration. In the present study, EUROSEM was used to simulate runoff processes on a single plane catchment.

The model requires two input files to run: a rainfall file that describes rainfall of a given storm; and a catchment file that describes the catchment characteristics. Altogether, both files require information on 62 variables and parameters with 9 and 53 in the rainfall and catchment files respectively (see appendices C and D). The variables and parameters describe climate, catchment geometry, catchment characteristics and channel characteristics. Rainfall and temperature are the only climatic variables required in the model. The temperature is used to calculate the kinematic viscosity of water.

EUROSEM gives the output in three file options: dynamic, static and auxiliary files. The output from the dynamic file is given in terms of storm hydrograph, total runoff, sediment graph, total soil loss and event summary. Static file summarises the input data, gives the erosion summary and the hydrology summary. The auxiliary file presents the interception data and diagnostic information.

EUROSEM has been used and applied in research and was found to simulate processes in a catchment quite reasonably. In the validation of the model using data from Woburn erosion sites in the United Kingdom, Quinton (1994) reported that the model performed well especially for the hydrology component (runoff, peak discharge and time to peak discharge). Some of the areas in which EUROSEM was applied include erosion studies in Europe (Morgan et al., 1994; Dempsey, 1996; Quinton, 1997; McCarthy, 1997; Morgan et al., 1998). The application of EUROSEM to studies under African conditions started only recently (Njiki, 1998; Mati, 1999). In the present study, the model was applied to runoff studies in the tropical semi-arid northeast Nigeria.

4.2 MODEL STRUCTURE

EUROSEM model has a modular structure with each module defining a separate process. Thus new research findings can be easily incorporated without major revision to the model. Figure 4.1 illustrates the complete structure of the model.

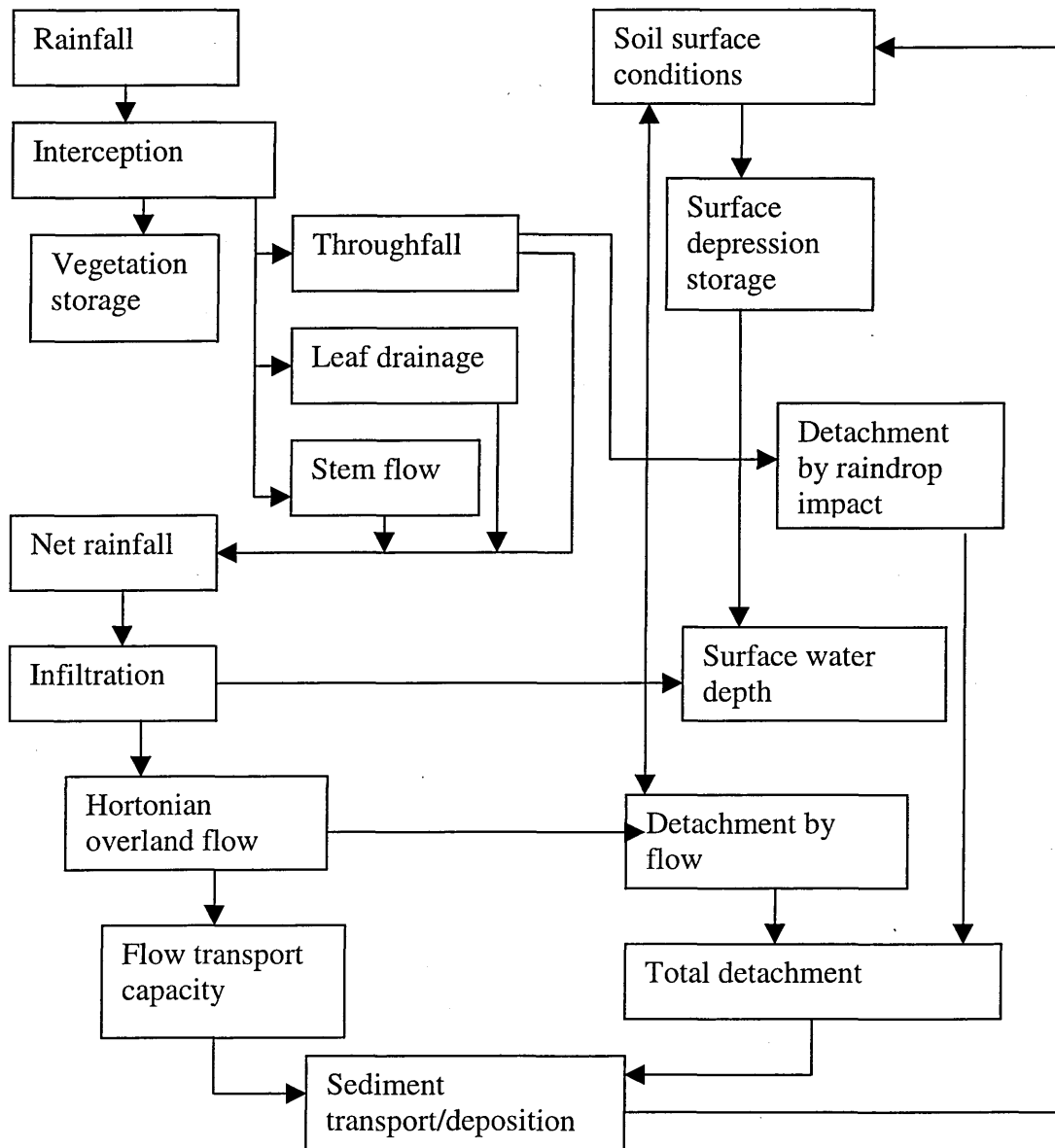


Fig. 4.1: The EUROSEM flow diagram (after Morgan et al., 1992).

Computations in EUROSEM is based on a numerical solution of the dynamic mass balance equation (Bennett, 1974; Kirkby, 1980; Woolhiser et al., 1990) given by equation 4.1.

$$\frac{\partial (AC)}{\partial t} + \frac{\partial (QC)}{\partial x} - e(x, t) = q_s(x, t) \quad (4.1)$$

where,

A = cross sectional area of the flow (m^2),

Q = discharge ($\text{m}^3 \text{s}^{-1}$),

t = time (s),

x = horizontal distance (m),

C = sediment concentration ($\text{m}^3 \text{m}^{-3}$),

e = net detachment rate of erosion of the bed per unit length of flow

($\text{m}^3 \text{s}^{-1} \text{m}^{-1}$) and,

q_s = extraction of sediment per unit length of flow ($\text{m}^3 \text{s}^{-1} \text{m}^{-1}$).

The different processes represented in the model include interception of rainfall by plant cover, runoff generation as infiltration excess, surface runoff, soil particle detachment by both raindrop impact and runoff, transport and deposition of sediment.

EUROSEM comprises two components; hydrology and erosion. In the present research, only the hydrology component is used and the erosion component is not described here.

4.2.1 Rainfall interception

The rainfall input to the model is in the form of a depth-time step during a storm. On reaching the vegetation canopy, some part of the rainfall is intercepted. The intercepted part is stored on the leaves and branches of the vegetation and this is modelled in EUROSEM as a function of the cumulative rainfall from the start of the storm, using the exponential relationship proposed by Merriam (1973):

$$IC_{st} = IC_{\max} \left[1 - \exp\left(-R_{cum}/IC_{\max}\right) \right] \quad (4.2)$$

$$IC_{st} = IC_{\max} \left[1 - \exp\left(-R_{cum}/IC_{\max}\right) \right]$$

IC_{st} = interception store (mm)

IC_{\max} = maximum depth of interception store for the given vegetation
cover (mm)

R_{cum} = cumulative rainfall (mm)

After the interception store is filled, the excess reaches the ground surface as either stemflow or leaf drainage. The volume of stemflow is modelled using the equation developed by van Elewijck (1989a; 1989b).

$$SF = 0.5 \text{ TIF } (\cos PA \cdot \sin 2 PA) \quad \text{for grasses, and} \quad (4.3)$$

$$SF = 0.5 \text{ TIF } \cdot \cos (PA) \quad \text{for other plant species} \quad (4.4)$$

where

SF = stem flow volume (m^3)

TIF = temporarily intercepted throughfall (m^3)

PA = average acute angle (-)

4.2.2 Infiltration process

The infiltration process is modelled in EUROSEM, as in KINEROS (Woolhiser et al., 1990), using the Smith and Parlange (1978) infiltration equation. The equation describes infiltration capacity as a function of the initial water content and the amount of rain already absorbed into the soil. The Smith-Parlange equation is given as:

$$f_c = \frac{K_s \exp \left(\frac{F}{B} \right)}{\exp \left(\frac{F}{B} \right) - 1} \quad (4.5)$$

$$\text{with } B = G (\theta_s - \theta_i) \quad (4.6)$$

$$\text{and } G = \frac{1}{K_s} \int_{-\infty}^0 K(\phi) d\phi \quad (4.7)$$

where,

f_c = the maximum rate at which water can enter the soil, (mm h^{-1}),

K_s = the saturated hydraulic conductivity of the soil (mm h^{-1}),

(represented by FMIN in the model)

F = the amount of rain already absorbed by the soil (mm),

B = water deficit parameter of the soil (mm).

G = the effective net capillary drive (mm),

θ_s = the maximum value of water content of the soil ($\text{cm}^3 \text{cm}^{-3}$),

θ_i = the initial value of soil water content ($\text{cm}^3 \text{cm}^{-3}$).

ϕ = the soil matric potential (mm), and

$K(\phi)$ = a hydraulic conductivity function (mm h^{-1}).

The process of infiltration is modelled through a single soil layer and comprises three stages. At the initial stage, infiltration is limited by the rainfall intensity and F is accumulated at the rainfall rate, and at this stage infiltration rate equals the rainfall rate. The second stage begins at the time when the infiltration capacity is reached, which is equivalent to the time of ponding. During this stage, the infiltration rate equals the infiltration capacity of the soil. The third stage begins when the rain ceases or the rainfall intensity falls below the infiltration capacity. Infiltration is then modelled as the infiltration capacity times the proportion of the soil surface covered by the flowing water (Morgan et al., 1998).

4.2.3 Surface runoff process

When the rainfall rate exceeds the infiltration capacity of the soil and surface depression storage is satisfied, the excess begins to flow down the slope as runoff. In EUROSEM, runoff along a slope of a plane, a rill or a channel is routed using the kinematic wave approach. The process is viewed as a one-dimensional flow process described by the Manning's, Chezy and continuity equations (equations 4.8 - 4.10). The Manning's equation is used in EUROSEM to calculate flow velocity for shallow overland flow.

$$U = \alpha pr^{m-1} \quad (4.8)$$

$$\text{with } \alpha = S^{\frac{0.5}{n}}$$

$$Q = \alpha pr^m \quad (4.9)$$

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = w[r(t) - f(t)] \quad (4.10)$$

where,

U = flow velocity (ms^{-1}),

r = hydraulic radius (m)

S = slope (%)

n = Manning's roughness coefficient ($\text{m}^{-1/3}\text{s}^{-1}$)

$m = 5/3$

p = wetted perimeter (m)

$Q = UA$ = discharge (m^3s^{-1})

A = cross-sectional area (m^2)

x = horizontal distance (m)

t = time (s)

w = flow width (m)

For a sheet interrill surface flow, a unit width is used for computations and the wetted perimeter becomes unity and the hydraulic radius equals the mean depth across the slope. Combining equations 4.9 and 4.10 yields equation 4.11 which is solved in EUROSEM using the Newton-Raphson numeric technique (Pearson, 1983; Woolhiser, 1990).

$$\frac{\partial A}{\partial t} + \alpha m h^{m-1} \frac{\partial h}{\partial x} = q(x, t) \quad (4.11)$$

where,

q = rainfall excess (m^2s^{-1}) and,

h = mean depth across the slope (m)

Flow is assumed over the entire element and the flow direction is directly down the plane.

4.3 SENSITIVITY ANALYSIS

4.3.1 Definition, uses and methods of sensitivity analysis

A first step in using a model must be an analysis of its sensitivity to various parameters (Silburn and Loch, 1989). Sensitivity Analysis is an evaluation of the relative magnitudes of changes in the model response as a function of relative changes in the values of model input parameters (Nearing et al., 1990). Sensitivity analysis reveals the relative importance of model parameters by ranking the model parameters based on their contribution to overall error in model predictions (McCuen, 1985). It can also provide insight into the nature of the model as well as insight into the factors that influence the response of a physical system once the model accurately represents the physical system that it simulates.

Perturbation and direct methods are most often used approaches to sensitivity analysis (Kabala and Milly, 1990). The perturbation method approximates sensitivities of output variables to the perturbed parameter by differential quotients based on two runs of the model, first with all parameters held constant and second with one perturbed. The direct approach involves differentiating the system of equations describing the model with respect to the parameters.

4.3.2 Objectives of sensitivity analysis

The aim was to study the influence on the output of errors or uncertainties in input data so that such data must be specified with great. Ranking model parameters according to model sensitivity helps in deciding which parameters can be obtained from the relevant literature and which ones should be measured in the field and to

what accuracy. Also, sensitivity analysis enhances better understanding of both the model and the system.

4.3.3 Choice of model output and rainfall event

Since the objective for using EUROSEM was to estimate runoff, the output considered in the sensitivity was therefore, the runoff volume. Rainfall event of 21st July 1994 (table 4.1) at Jawa was used for the simulation. This rainfall event was chosen because of its size and the distribution of its intensity. The total rain was 44 mm and its duration was more than 3 hours. Intensity within the storm varied from low to moderate.

Table 4.1: Summary of rainfall distribution at Jawa on 21/07/94.

Cumulative time, min.	Cumulative rainfall, mm	Average intensity, mm/h
0	0	0
20	2.4	7.2
30	8.6	17.2
40	24.2	36.3
50	32.8	39.4
60	35.6	35.6
70	38.4	32.9
97	40.4	25.0
201	44.4	13.3

For the parameters in the catchment file of the model, base values were selected based on field observations and those suggested in the EUROSEM userguide (Morgan et al., 1993). As the *fako* lands are devoid of vegetation and contain no rills, the parameters describing cover and vegetation were assigned zero values.

4.3.4 Sensitivity statistics

A variety of statistics is available to describe model sensitivity. When a model output takes the form of a single value, sensitivity can be evaluated using any of the following methods: absolute sensitivity (McCuen, 1973), relative sensitivity (McCuen, 1973), average linear sensitivity (Nearing et al., 1989) or the subjective method. The subjective method involves visual comparison of graphical plots (Li et al., 1977). In this exercise, total runoff volume from the simulations was processed using the average linear sensitivity (ALS). The ALS is a modification of the relative sensitivity and it represents a relative normalised change in output to normalised change in input (equation 4.12). According to Nearing, et al. (1989), the ALS is a valid means of comparing sensitivities for different input parameters that have different orders of magnitude. Quinton (1994) used this approach.

$$ALS = \frac{\frac{O_2 - O_1}{O_{12}}}{\frac{I_2 - I_1}{I_{12}}} \quad (4.12)$$

Where,

I_{12} and O_{12} are the averages of the inputs I_1 & I_2 and outputs O_1 & O_2 respectively.

4.3.5 Result of sensitivity analysis

Ranked in descending order, table 4.2 shows the sensitivities of hydrology parameters to runoff volume from the EUROSEM model. The table also shows the range of input for each parameter over which the sensitivity was calculated.

Table 4.2: Some hydrology parameters of EUROSEM model with their base values, range of test and ALS sensitivity statistic.

Parameter	Unit	Base value	Range of test	ALS
THMX	$\text{cm}^3 \text{cm}^{-3}$	0.38	0.152 - 0.400	-0.658
G	mm	540	216 - 972	-0.410
FMIN	mm h^{-1}	4	2 - 20	-0.212
THI	$\text{cm}^3 \text{cm}^{-3}$	0.131	0.052 – 0.256	0.201
MANN	-	0.03	0.01 – 0.06	-0.01
POR	fraction	0.4	0.4 – 0.7	0.006
RECS	mm	10	4 - 18	0.001

It can be seen from the table that the model is sensitive to four parameters as far as runoff volume is concerned. The negative sign in the table indicates an inverse relationship between runoff volume and the parameter in question. Maximum relative saturation (THMX) and effective net capillary drive (G) are the most sensitive parameters to which EUROSEM responds. The respective ALS values for THMX and G were -0.658 and -0.410. Saturated hydraulic conductivity (FMIN) and initial relative saturation (THI) follow next with ALS of -0.212 and 0.201 respectively. The sensitivities of the model to the other parameters are rather slight with ALS ranging from 0.001 for RECS to 0.010 for Mann.

The first four parameters (THMX, G, FMIN and THI) were most sensitive because they are the principal elements controlling infiltration of water into the soil as described by equations 4.5 - 4.7 in section 4.2.3. The water deficit parameter is a function of the difference between the maximum and initial values of relative saturation of the soil. It can be seen that infiltration capacity changes exponentially with B (equation 4.6). Infiltration capacity increases as saturated hydraulic

conductivity is increased and consequently the time to runoff is increased which eventually decreases the total volume of runoff.

Compared to the sensitivity result of Quinton (1994), there is a variation in the ranking of the parameters as well as in the values of the sensitivity statistics. For example, Quinton (1994) found the ALS value for THMX was -2.6 and the THI followed in ranking with ALS of -1.2. These values were higher than what was obtained in this analysis. The rainfalls used in the sensitivity analysis in Quinton (1994) and in this analysis were responsible for the variation. For the rainfall used in this study, the intensity distribution was such that it was low at the beginning of the storm and only became high enough to cause runoff 30 minutes after the start of the rain. The low intensity rain during the early 30 minutes dampened, to some extent, the effect of varying THI. The deficit between THMX and THI was reduced by increase in THI before the start of the runoff-producing intensity. As moisture deficit decreases, f_c tends to the value of K_s . The long early low intensity part of the rain, brought the values of THI and THMX close together and thereby made ALS of G close to that of THMX.

Manning's roughness affects runoff mainly through the flow velocity rather than volume as expressed in another form by the following:

$$U = (S^{1/2} r^{2/3}) / n \quad (4.13)$$

Where, U, S, r and n are as defined earlier.

As n is increased U decreases, which means that more time is taken for the water to flow down the plane and hence more of the water will infiltrate into the soil with resultant less runoff.

4.3.6 Summary of Sensitivity Analysis

The parameters THMX, G, FMIN and THI are the most sensitive in EUROSEM model as far as runoff generation on the soil surface is concerned. Therefore, all but G were estimated either on the field or in the laboratory as explained in chapter three.

For the less sensitive parameters, it means that their influence on runoff volume is not much and therefore, coarse estimates of these parameters can be used with correspondingly smaller errors in estimating the runoff volume. The values of some of the less sensitive parameters were obtained from relevant literatures.

4.4 CALIBRATION AND VALIDATION

4.4.1 Introduction

For a model to be used and in order to have confidence in its results, predictions from the model have to be validated against field data. It is important that the results from a model are objectively validated to ensure that the model is performing adequately for the task to which it is being applied. The procedure followed in this study involved, first calibrating the model and then validating it using field measurements (Klemes, 1986).

The runoff data from the simulated rain in table 3.2 of chapter 3 was divided into two parts, ensuring as much as possible equal spread of the range of intensities in both parts. EUROSEM model was calibrated with one part of the data and then validated with the other part.

In order to compute runoff volumes, the measured runoff flow rates were first plotted against their corresponding times to obtain hydrographs. The best description of the hydrographs was given by logarithmic function. The logarithmic function describing each flow was integrated to yield the observed runoff volume (V) (equation 4.14)

$$V = \int_{\alpha}^{\beta} [m \ln(x) + c] dx \quad (4.14)$$

Where

α and β are the lower and upper time intervals respectively within

which the flow rates were measured

m & c are the slope and intercept of the graph obtained respectively.

The corresponding predicted runoff volumes were obtained from simulations by the EUROSEM model. Two simulations with the EUROSEM model were carried out for each rainfall event. The first simulation represented the entire duration (β) of the rainfall and the second represented the period (α) before the start of measurement. The corresponding predicted runoff volumes were therefore, obtained by subtracting the volume obtained at time = α from that at time = β .

4.4.2 Calibration

Three hydrology parameters of the model were subjected to systematic variation in the calibration exercise. The parameters were maximum relative saturation of the soil (THMX); porosity (POR) and net capillary drive (G). THMX and POR were chosen because their field values were found to be within some range and therefore, they were varied within their ranges. The parameter G was chosen because it is difficult to measure it on the field or in the laboratory, and it was varied within the range specified in the EUROSEM User Guide (Morgan et. al, 1993). Both THMX and G are sensitive as far as runoff is concerned. All other parameters were left at their measured or base values.

Calibration was achieved by comparing results with alternative parameter values to find those that optimize the fit of predicted runoff volume to observed runoff volume (table 4.3).

Table 4.3: Observed runoff volumes used in calibration. Where α and β are the time between which measurements were taken after the start of rain.

Site	Rainfall intensity (mm/h)	Runoff volume (lit)	α (min)	β (min)	Average discharge/unit area, q (mm/h)
Jawa	36	1.37	18	32	2.0
	60	13.59	2	15	20.9
	60	14.64	3	15	24.4
	65	19.38	13	26	29.8
	145	44.2	2	13	80.4
	169	61.5	2	18	76.9
Zurkaya	127	58	4	17	89.2
	50	10.9	6	17	19.8
	37.5	11.1	13	29	13.9
	41	6.8	11	21	13.6
	135	46.22	0	11	84
	32	12.6	6	17	22.9
Dumburi	41	17.3	3	16	26.1
	52.5	9.8	21	34	15.1
	72	16.7	2	14	27.8
	145	57.3	2	12	114.4

The method of ordinary least squares was used to estimate parameters with the minimum sum of squares, G (Green and Stephenson, 1988). When G is minimised, the fit is optimal and the corresponding value of the parameter could be used with the model to predict output from the input.

4.4.3 Validation

Validation of the model was conducted on the second part of the runoff data (table 4.4). With the optimum values obtained in calibration, runoff volumes for the second part of the data were predicted with the model. The predicted and measured runoff volumes were then compared. After validation the model was evaluated.

Table 4.4: Observed runoff volume used in validation. Where α and β are the time between which measurements were taken after the start of rain.

Site	Rainfall intensity (mm/h)	Runoff volume (lit)	α (min)	β (min)	Average discharge/unit area, q (mm/h)
Jawa	25	0.5	8	22	0.7
	32	4.0	11	25	5.7
	45	12.9	16	30	18.4
	54	17.5	4	15	31.9
	156	30.5	4	10	101.6
Zurkaya	142	29.2	2	10	73.0
	156	38.4	3	10	109.7
	162	12.3	3	8	49.2
	50	12.4	0	13	19.1
	58	7.6	3	10	21.7
Dumburi	120	25.4	5	12	72.6
	65	13.2	3	13	26.4
	48	20.8	14	31	24.5
	32	13.1	4	20	16.4

4.4.4 Model Evaluation

There are various methods of evaluating the performance of models depending on the type of model, data available for testing and the ultimate purpose for the model. Evaluation of the EUROSEM model was carried out by graphical and analytical methods (ASCE, 1996). After obtaining the best set of parameters, quantitative assessment of the model using the following statistical goodness-of-fit criteria were carried out:

1. Root mean square error (RMSE),

$$\text{RMSE} = \left[\frac{1}{n} \sum_{i=1}^n (x_i - y_i)^2 \right]^{\frac{1}{2}} \quad (4.15)$$

Where;

y_i = simulated value

x_i = measured value

n = number of data pairs

The RMSE gives the average error between the measured and predicted values.

2. Coefficient of efficiency (E),

$$E = 1 - \frac{\sum (x_i - y_i)^2}{\sum (x_i - x_m)^2} \quad (4.16) \quad (\text{Nash and Sutcliffe, 1970})$$

where;

x_m = mean measured value

The coefficient of efficiency provides a dimensionless measure of model performance. The value of E can range from 0 to 1, with 1 indicating a perfect fit and a zero value implies that the mean of the observed values provides a better prediction than the model does.

3. Accuracy (ACC).

$$\text{ACC} = \left[\frac{1}{n - p} \sum_{i=1}^n (x_i - y_i)^2 \right]^{\frac{1}{2}} \quad (4.17) \quad (\text{ASCE, 1996})$$

where;

p = number of predictor variables

4. Coefficient of determination (R^2): This measures the degree of association between observed and predicted measurements. It does not however, reveal systematic errors. The value of R^2 is always less than unity.

4.4.5 Result of Calibration and Validation

Table 4.5 shows the calibration parameters and their range values. The range of the maximum relative saturation of the soil was obtained from the water release data at a pressure of 0 kPa. Figure 4.2 shows a plot of various values of THMX versus sum of squared residuals (SS) and how the optimum THMX value of 0.41 with the least SS was selected.

Table 4.5: Calibration parameters for sandy clay-loam and clay-loam soils

Parameter	Range
porosity	0.33 - 0.52
maximum relative saturation of the soil	0.33 - 0.49
net capillary drive of the soil	220 - 1174 mm

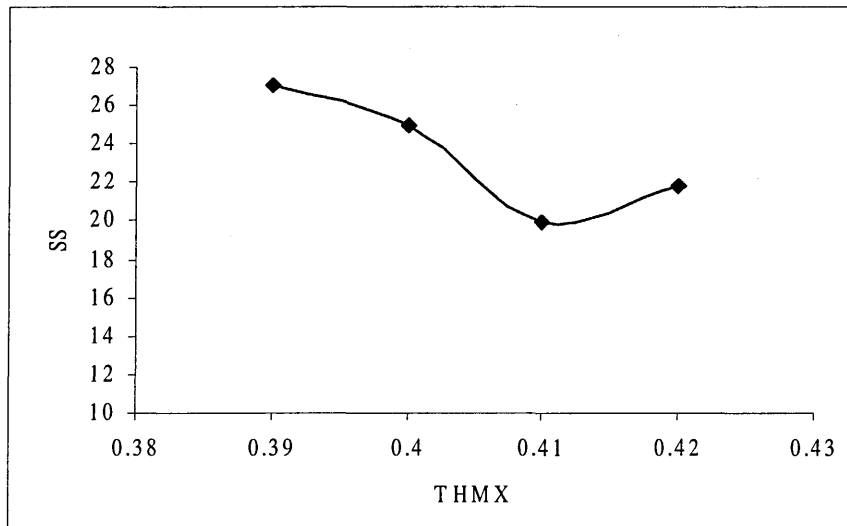


Fig. 4.2: Plot of THMX values against sum of squared residuals (SS) showing a value of 0.41 for the minimum SS.

Table 4.6 shows the field geometry and hydrology parameter values after calibration of the model. Except for a few parameters that were obtained from the EUROSEM userguide (Morgan et al., 1993), most of the parameters were measured.

After the calibration, continuous time series plots show quite good agreement between measured and predicted. A pair of hydrographs for high and low intensities is presented for one site (figure 4.3) as an example, and a general overview of the model performance can be seen.

Table 4.6: Input parameter values used in model simulation for the 3 sites.

Parameter	Input value	Remarks
Plot length	2.0 m	measured plot
plot width	1.5 m	measured plot
slope	0.5%	measured in the field
interrill Manning's n	0.02	obtained from User Guide (Morgan et. al, 1993)
saturated hydraulic conductivity	4.0 mm _h ⁻¹	measured average for all fako sites
net capillary drive	340 mm	average calibrated value for all sites
maximum volumetric soil water content	0.41	average calibrated value for all sites.
initial volumetric soil water content	variable	measured in the field
porosity	0.43	average calibrated value for all sites
proportion of the soil occupied by stones	0.0	observed in the field
infiltration recession factor	10.0	obtained from User Guide (Morgan et. al, 1993)
median particle size of the soil	250µm	obtained from User Guide (Morgan et. al, 1993)

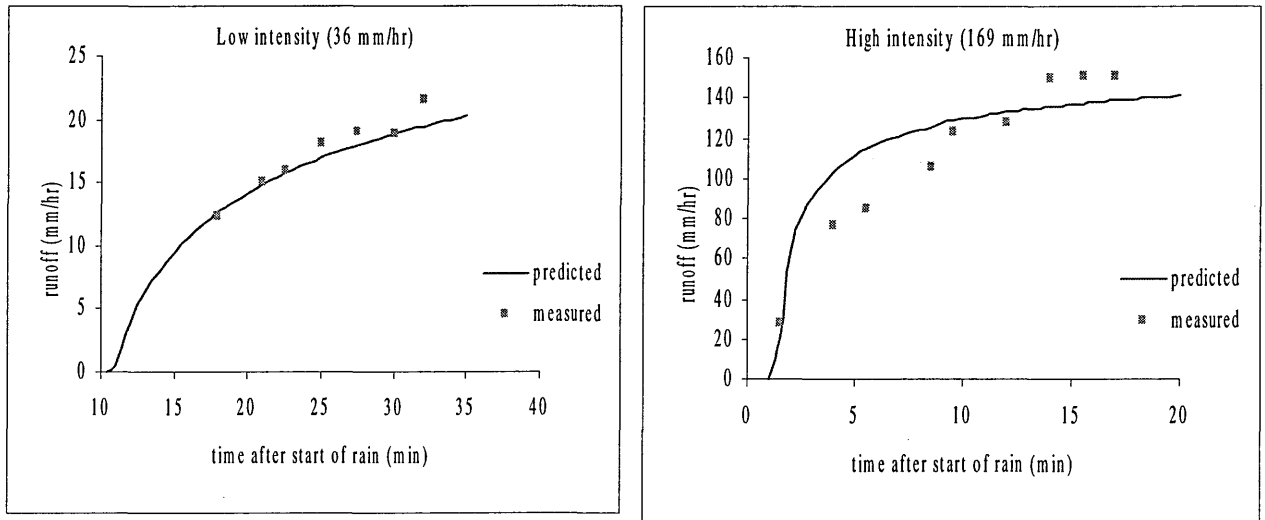


Figure 4.3: An example of visual assessment of the model with low intensity (36 mm_h⁻¹) and high intensity (169 mm_h⁻¹) rain at Jawa site.

The runoff flow rate from the low intensity storm appears to be better simulated than that from the high intensity storm. This may be due to two reasons. First, different nozzles were used for the two intensities in the artificial rains. The nozzle used for the high intensity storm produced bigger drops with higher coefficient of variation in the distribution of intensity across the plot. This is likely to cause error in the actual value of the intensity of the artificial storm. The second reason may be due to variation in soil condition during the storm event. The soil surface condition during the later part of a high intensity storm may become sealed due to raindrop impact and assorting action of the flowing water. This dual field scenario during a single event is not reflected in the model, thereby varying slightly with the field situation.

The scatter plot (figure 4.4) shows the agreement between observed and predicted pairs of runoff volumes for the calibration and validation.

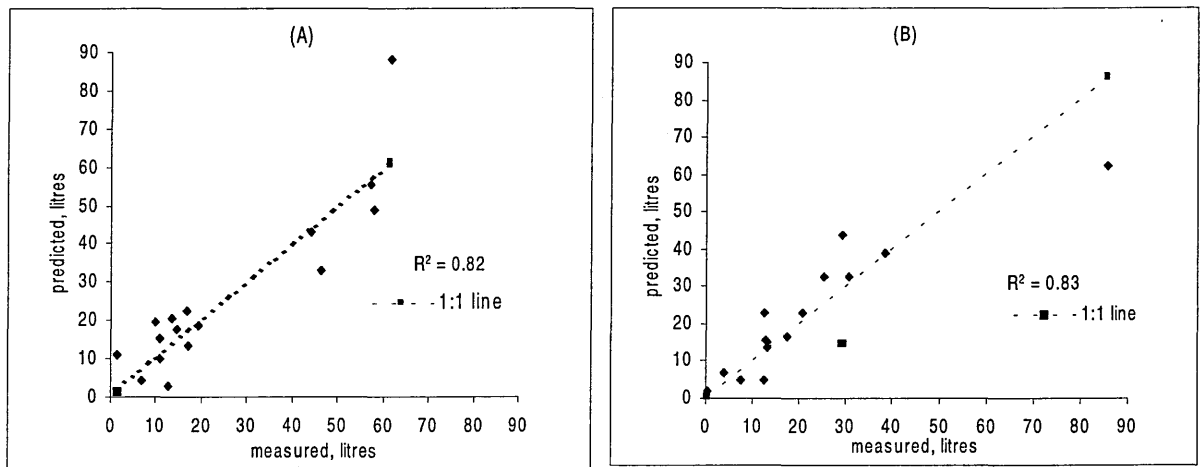


Figure 4.4: Relationship between measured and predicted values of runoff volume in calibration (A) and validation (B).

The statistical indices of assessment of calibration and validation of the model are presented in table 4.7. The table shows the assessments of both runoff volume and runoff flow rate. Linear regression between predicted and observed runoff volume gave R^2 values of 0.82 and 0.83 for calibration and validation respectively. For the flow rate the R^2 were the same at 0.88 in both cases.

Table 5: Statistical measures of goodness-of-fit for runoff volume in calibration and validation.

Criterion	Runoff volume		Runoff flow rate	
	calibration	validation	calibration	validation
ACC	9.56	8.6	0.23	0.26
E	0.82	0.74	0.88	0.88
R^2	0.82	0.83	0.88	0.88

The model performed as well over the validation set as it did over the calibration (see table 5). The result in the calibration set is similar to that of the validation set, and therefore the model can be considered stable and is capable of estimating runoff volume quite well on the *fako* lands. Generally, the prediction of the runoff flow rate was slightly better than the runoff volume. This is expected because the runoff volumes were computed from approximations based on the flow rates.

EUROSEM uses the kinematic wave approximation method to route runoff across the soil surface (Woolhiser, 1970; Kibler and Wool, 1970; Woolhiser and Liggett, 1967). The calibration parameters (THMX, G and POR) are the hydrology parameters that affect the generation of runoff. They all, together with hydraulic conductivity function, determine the infiltration capacity of the soil as described by equations 4.5 - 4.7. Volume and time distribution of runoff are determined through the surface roughness coefficient (Manning's n), effective saturated hydraulic conductivity, effective net capillary drive and initial water content of the soil.

4.5 LIMITATIONS OF THE EUROSEM MODEL

Some notable limitations of the EUROSEM model in the context of the present study include the following:

1. The model does not include in its structure the process of evapotranspiration and therefore cannot simulate periods between events. The model can be used for single events only and this requires that the starting conditions for each storm be specified as data inputs.
2. In order to obtain accurate results, the model requires very detailed catchment data and high-resolution rainfall data.

4.6 CONCLUSION ON EUROSEM MODEL

Sensitivity analysis on the EUROSEM model revealed that the parameters, which affect infiltration of the soil, are the most sensitive parameters in the model as far as runoff is concerned. These parameters are maximum relative saturation of the soil, effective net capillary drive, saturated hydraulic conductivity and the initial relative saturation of the soil.

The model was calibrated and validated using field data. Calibration of the model was based on varying three parameters (maximum relative saturation, porosity and effective net capillary drive) within their range values until best fit between observed and simulated was achieved. Validation was achieved by comparing predicted runoff volumes with observed data not used in calibration. After validation, the model was evaluated and the summary statistics confirmed that it could adequately simulate surface runoff on the *fako* lands of northeast Nigeria. Quinton (1994) reported result of his validation that also showed good agreement between measured and simulated runoffs.

CHAPTER FIVE

THE BALANCE MODEL

5.1 INTRODUCTION

A comprehensive water balance computer simulation model should be able to integrate climatic factors (precipitation, atmospheric evaporation demand), soil factors (water holding capacity, water infiltration and redistribution, soil evaporation) and crop factors (canopy development, transpiration, soil water uptake). BALANCE is one such model and it is a mechanistic, one dimensional computer simulation model written by Hess (1994) to estimate the daily soil water balance for a cropped or uncropped surface using daily rainfall and reference crop evapotranspiration. It is mechanistic, in that it basically satisfies the law of conservation of matter. Input of water (rainfall and irrigation) over a given time is precisely balanced by the loss of water (runoff, evapotranspiration and drainage) and/or by a change in the amount of water stored within the soil unit. All the five components of the water balance (net precipitation, surface runoff, evapotranspiration, drainage and change in profile water content) play important roles within the ecosystem of arid and semi arid areas (Walker et al., 1986; Winter et al., 1989; Bozzo et al., 1992). It is therefore important to have long term and continuous records of scientifically credible data of these components for sustainable development of water resources.

The model has been applied and tested on the sandy soils of Maiduguri in northeast arid zone of Nigeria (Hess, 1999). In order to have reliable estimates of these components from the BALANCE model, the model should be tested and evaluated first. The objectives in this chapter therefore, were:

1. to conduct sensitivity analysis of the model with a view to identifying the sensitive parameters that should be accurately determined.
2. to calibrate and validate the model with field data

3. to evaluate the model and determine its suitability for application in subsequent studies in the area.

To achieve the above objectives, sensitivity of the model to each parameter was first assessed to determine the most sensitive ones (Silburn and Loch, 1989) so that their values be determined (whether in the field or in the laboratory) with as much accuracy as possible. Change in soil moisture content was used to calibrate the Ritchie (1972) equation, which BALANCE uses for evaporation process. The moisture content data was divided into two parts. One part was used for the calibration and the other for validation (Klemes, 1986). After the calibration and validation, statistical indices were used to evaluate the model.

5.2 BRIEF DESCRIPTION OF THE BALANCE MODEL

Complete description of the structure of the model and the methods used in describing the different processes contained in the model is given in appendix E and only a brief description is presented here.

The BALANCE model uses the input of rainfall and/or irrigation to estimate evapotranspiration, runoff, soil moisture and drainage out of the root zone. It sums up the gains and losses on each day. The model estimates actual evapotranspiration by summing up actual soil evaporation, actual crop transpiration and evaporation from mulch cover. Actual soil evaporation in the model is based on the Ritchie (1972) equation while actual transpiration is based on potential transpiration and crop cover fraction. The actual transpiration can fall below the potential level on dry days. Evaporation from mulch cover is assumed to occur only on days when the mulch is wetted by rainfall or irrigation. Runoff is estimated using the Soil Conservation Service curve number method by adjusting the curve number according to antecedent moisture condition of the soil on each day. Drainage is estimated in the model on the basis of the soil water holding characteristics.

BALANCE requires three input files to estimate the various components of the water balance on daily basis. The files are meteorological, soil and crop data files. The

meteorological file is externally created and consists of the daily weather data. The weather data required are daily rainfall and evaporation. The crop and soil input files define the crop and soil characteristics respectively, and they can be created in the programme using the interactive editor. The parameters of the crop file include planting depth/date, harvest dates, rooting depth and crop factors. The soil file describes water holding characteristics and soil evaporation parameters.

The water balance output can be produced in the form of daily, decadal or monthly totals. The model gives its output in three files. The files contain summary of the crop and soil data, details of the water balance and annual summary.

5.3 SENSITIVITY ANALYSIS

Sensitivity of the BALANCE model to parameters and variables was analysed as was done for EUROSEM model (chapter four). The objective here also, was to identify the most sensitive parameters and variables with a view to estimating them accurately so that errors resulting from their measurements were minimised. Until recently, the application of sensitivity analysis to unsaturated flow problems has been minimal (Kabala and Milly, 1990). The procedure has now become useful tool for understanding and solving problems in unsaturated flows. Using perturbation method, Freshley et al. (1982) computed the sensitivities of drainage to such parameters as precipitation, hydraulic conductivity and potential evaporation for unsaturated flow in homogeneous media. Kool and Parker (1988) used elementary sensitivity analysis to solve the inverse problem for unsaturated homogeneous soils.

5.3.1 Input parameters and variables for sensitivity analysis

For the meteorological data file of the model, rainfall of 1962 was chosen for the sensitivity analysis. The year had a rainfall total of 432.2mm, which is closest to the average (435mm) of a thirty-year period (1961 – 1990) for Nguru station. The reference crop evapotranspiration used varied between months and ranged from 4 mm/day in December to 7.0 mm/day in April. These values were based on long-term monthly averages for the area (Hess, 1998). The values are similar to the ranges reported in other arid and semi-arid areas [6.3 – 7.2 mm/day for pastures and

rangelands in the USA (Shih and Snyder, 1985; Kopec et al., 1988), and 3 – 6.4 mm/day for rangeland in Australia (Christie, 1978; Dunin and Reyenga, 1978)].

Base values for parameters and variables in the soil and crop files used in the sensitivity analysis were obtained from laboratory estimates, literature and personal communications (table 5.1).

Table 5.1: Base values for parameters and variables used in the sensitivity analysis of BALANCE model.

Parameter	Unit	Base value	Range
U, amount of water that can be evaporated at potential rate	mm	10	6-14
α , rate of decay of soil evaporation	mm/day ^{1/2}	4.2	2.5-5.8
τ , drainage constant	-	0.26	0.16-0.36
CN, curve number	-	80	48-100
θ_s , volume water fraction at saturation	cm ³ /cm ³	0.43	0.26-0.60
θ_f , volume water fraction at field capacity	cm ³ /cm ³	0.30	0.18-0.40
θ_p , volume water fraction at permanent wilting point	cm ³ /cm ³	0.15	0.09-0.21
θ_i , initial moisture content	cm ³ /cm ³	0.15	0.09-0.21
p, fraction of total available water that is easily available to plant	-	0.50	0.30-0.70
K _c , crop coefficient	%	70	42-98
M _c , mulch cover	%	50	30-70

5.3.2 Choice of model output

The model was intended to be used for estimating water balance components. Sensitivity analysis using one or more of these components (precipitation, runoff, evapotranspiration, drainage and change in soil water, except for precipitation, which is one of the inputs driving the model) as the objective function is justifiable. Runoff, evapotranspiration and soil water were the most important components of the water balance equation as far as this part of the research was concerned. Runoff was not taken as output here because it was considered separately using a different model (see chapter four), and also it was envisaged that runoff was to be controlled in the simulations. It was therefore, decided that actual transpiration be used in sensitivity analysis and the soil water content in calibration and validation of the model.

5.3.3 Parametric sensitivity

Each of the eleven parameters from the input soil file and crop file was varied between 60 % and 140 % of its base value at 20 % intervals. Simulation was conducted for each unique parameter value and the corresponding output of actual transpiration recorded. Average linear sensitivity (Nearing, et al., 1989) was used to determine the sensitivity of the model to each parameter (equation 4.12) and then the parameters were ranked.

5.3.4 Results and discussion of sensitivity analysis

A plot of actual transpiration (T_a) versus percentage of base value for each parameter (figure 5.1) reveals the extent of sensitivities of the model to the various parameters. The slope of each parameter indicates its level of sensitivity. Ranked in ascending order, θ_f , θ_p and θ_i are the most sensitive parameters in the model as far as actual transpiration is concerned. The crop coefficient and mulch cover follow next with ALS values of 0.26 and 0.14 respectively. Soil hydraulic parameters, p , θ_s , α and U were found to be moderately sensitive. The ALS values of these moderately sensitive parameters ranged between 0.05 to 0.1. The drainage constant (τ) was found to be the least sensitive parameter to the model in this environment.

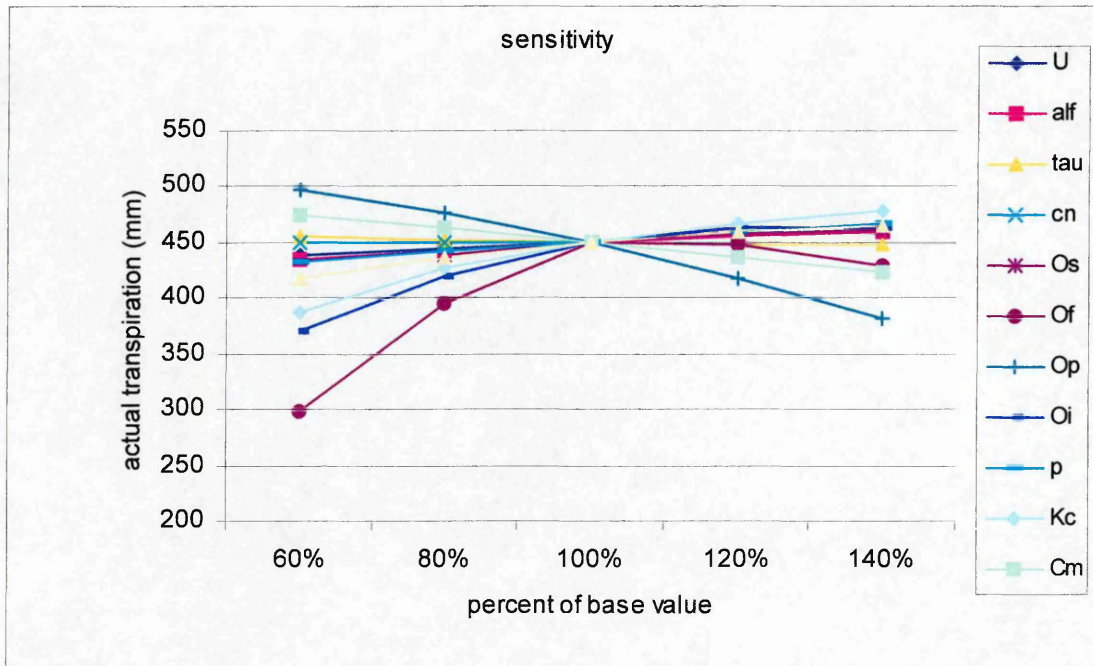


Figure 5.1: Sensitivity in transpiration of BALANCE model to various parameters of the model.

Crop growth can be directly related to its water use. The initial moisture content of the soil and the moisture contents at field capacity and at permanent wilting point were most sensitive because actual transpiration is a function of the available water capacity. The parameters, θ_f and θ_p control the available water in soil for the plant to utilize for transpiration (Klute, 1986; Lal, 1991). If the soil moisture content at field capacity is increased while the rest of the parameters are kept constant, the soil water holding capacity will be increased and therefore, more water will be available to the plant.

Some of the parameters showed non-linearity in the sensitivity when increased from low to higher values. At low values, the parameter θ_f showed high sensitivity and then became less at high values as can be seen in figure 5.1 above. This is because

the soil water is affected in two ways. At low value, the soil, in addition to having less capacity to hold water for the plant, is accompanied with drainage caused by increase in the drainable porosity (equation 5.1).

$$dr = \tau(\theta - \theta_f)(e^{(\theta - \theta_f)} - 1)/(e^{(\theta_s - \theta_f)} - 1) \times 1000 \text{ mm/m} \quad (5.1)$$

where,

dr = drainage from layer in mm/m of layer thickness/day

τ = drainage constant

θ = volume water fraction

θ_f = volume water fraction at field capacity

θ_s = volume water fraction at saturation.

As θ_f is increased, drainage becomes less effective as can be seen from equation 5.1 and the easily available water capacity increases and approaches the potential rate of transpiration. The situation with θ_p is similar but opposite to that of θ_f with respect to the soil available water.

Transpiration was insensitive to CN at values from 60 to 100 % of the base value as it cannot go beyond 100 %. At low values of CN, runoff does not occur and the situation in the soil remains unchanged. Runoff will occur only when the threshold value is reached, and any increase beyond the threshold value will affect the amount of water going into the soil store and this will in turn affect transpiration.

The drainage constant has a direct relationship with drainage (equation 5.1) and only affect transpiration indirectly again through the soil available water. Transpiration showed little sensitivity to the drainage constant because there was less drainage as a result of the set of base values used. The values used imply high water holding capacity of the soil. Also, the rainfall data used in the analysis had, for the rainy period June to September, a relatively long average dry spell (average interval between raindays). The average dry spell for this period was three days. These two

conditions (high water holding capacity and long dry spell) did not favour drainage and therefore, τ had no significant effect on the available soil water.

5.3.5 Summary of sensitivity analysis

Soil physical properties exert a dominant effect on soil-water balance and water use efficiency especially in areas prone to drought stress (Lal, 1991). Sensitivity analysis of the BALANCE model showed, for a particular weather scenario, plant transpiration is affected most by the soil properties, e.g. field capacity and permanent wilting point. These two soil parameters affect the plant-available water reserve and therefore, they determine the water that is easily available to the plant. Also of significant importance are the crop coefficient and the amount of mulch cover. The parameters defining soil saturation and soil evaporation are moderately sensitive in the model. Due to little or no drainage out of the profile as a result of the soil condition used, the drainage constant was found to be least sensitive as far as actual transpiration is concerned.

5.4 CALIBRATION AND VALIDATION OF THE RITCHIE EQUATION

No matter the complexity of a computer simulation model, it is a simplified representation of the actual conditions on the field and thus can only represent actual conditions to some degree of accuracy. Accuracy of a model and its results is determined by how well the different actual processes are represented in the model and by the quality of available input data. In order to have confidence in the model, its ability to simulate the soil-plant-atmosphere continuum (to predict the changes in soil water content with time under a given climatic, soil and crop conditions) was tested on the evaporation process. This was carried out using profile moisture contents of the bare soils (without vegetation) of Jawa and Zurkaya sites monitored over a time period of three months.

5.4.1 Weather file

Weather data files for the period of the experiment were created. Each file contains five columns, with the first three for date (day, month and year) and the two others for rainfall and reference crop evapotranspiration. No natural rainfall occurred during

the study period and therefore, only the amount of water applied during the initial three days of setting up the experiment was reflected. There was no daily evapotranspiration data but however, daily pan evaporation data was available. The daily pan evaporation data is changed to daily evapotranspiration by the model using a pan coefficient. A pan coefficient of 0.5 was used. This is the value for a pan placed in dry fallow area with low mean relative humidity and light wind speed of less than 40% and 175 km/day respectively (FAO, 1992).

5.4.2 Soil and crop files

There was no vegetation on the experimental areas and therefore, the crop file of BALANCE was made bare by setting all the parameters in the file to zero.

The parameters of the soil file were assigned their measured or estimated values. For the purposes of description here, the soil file can be viewed in two parts. One part can be taken as that which describes the water holding capacity of the soil and the other as that which describes the soil evaporation process. The major parameters that describe the water holding capacity of the soil are θ_s , θ_f and θ_p and were determined in the laboratory from undisturbed cores using the sand table and pressure membrane apparatus as described earlier under chapter three. For the second part, the parameters that describe the soil evaporation process are U and α (Ritchie, 1972), and they were the parameters used in calibration.

5.4.3 Calibration

Measured soil moisture data for the three treatments (bare, partial cover and solid cover) in section 3.2.2 of chapter 3 was divided into two parts with one part used for calibration and the other for validation (Klimes 1986). The soil moisture content of two of the three replicates for Zurkaya site and one of the three for Jawa site were used for calibration. The remaining one replicate for Zurkaya and the two others for Jawa site were used for validation. Model predictions were compared with these field measurements and then evaluated.

The measured moisture content data was calibrated on the Ritchie (1972) equation that describes evaporation process (equation 5.2). Empirical soil parameters U and α in the Ritchie equation were used for the calibration.

$$Es_i = \alpha t^{1/2} - \alpha(t-1)^{1/2} \quad (5.2)$$

where,

α = constant, (mmday^{-0.5}) and,

t = time in days since last rain in excess of potential soil evaporation.

Change in soil moisture content was assumed to be due to evaporation only as there was no drainage observed and no growing plants at the sites. The moisture content data was plotted against time and then fitted with a smooth curve. Figure 5.2 shows smooth curves fitted through average moisture contents for the three treatments for Zurkaya site. Daily moisture contents were then obtained from the smoothed curves by interpolation. These were carried out for the three treatments. The first stage (constant rate) was separated from the second stage (falling rate) by visual observation of the graph. The daily moisture content of the second stage was used to estimate the value of α using equation 5.3 (Black et al., 1969):

$$\sum E_{s2} = \alpha t^{1/2} \quad (5.3)$$

where;

$\sum E_{s2}$ = cumulative evaporation in the second stage (mm)

Estimated cumulative evaporation (change in soil moisture content) was compared with that calculated from equation 5.3 by assigning values for α . The best value for α was determined by iterative technique. Microsoft Excel Goal Seek was used to minimize the root mean square of the difference between the estimated and calculated cumulative evaporation. This procedure was repeated for the other treatments of partial and solid covers (see section 3.2.2 of chapter three).

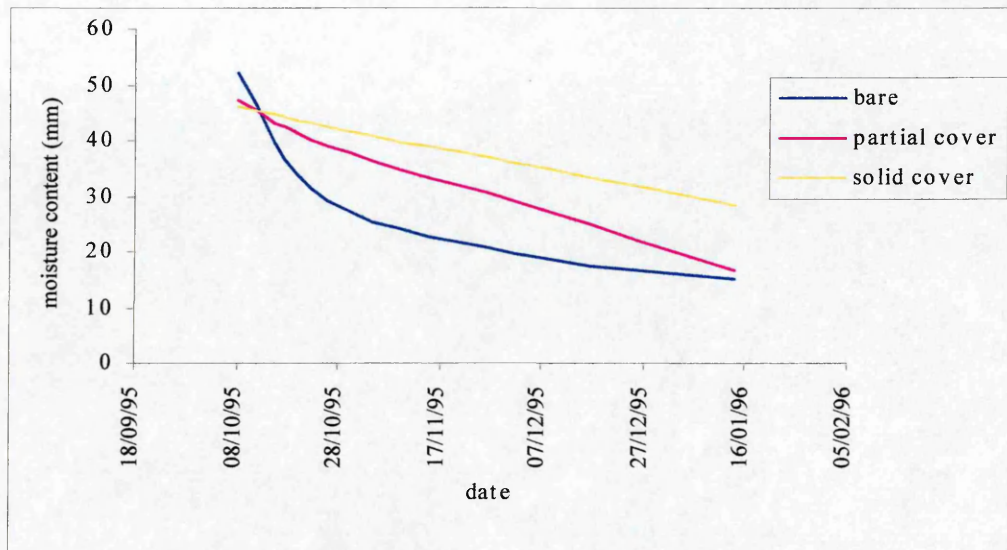


Figure 5.2: Variation of soil moisture content with time at Zurkaya site.

Simulation runs for the period of the experiment were then carried out for each treatment. Values of U and α were adjusted to give the best fit of the soil moisture content to the observed data. For the validation, the parameter values obtained after calibration were used and the model was run to simulate the profile moisture content of the second part of the data.

5.4.4 Result and discussion of calibration and validation

The U value obtained after calibration was 19 mm for the bare treatment and 20 mm each for perforated and solid cover treatments. The calibrated α values for the bare, partial and solid cover treatments were $4.5 \text{ mmday}^{-0.5}$, $2.2 \text{ mmday}^{-0.5}$ and $0.5 \text{ mmday}^{-0.5}$ respectively. A complete list of parameters and their measured or calibrated values is presented in table 5.2.

Table 5.2: Soil file parameters of BALANCE and their values obtained after calibration.

Parameter	Value			Remarks
Profile depth (cm)	30			determined in the field
Saturation moisture content (θ_s)	0.43			determined in the laboratory
Moisture content at field capacity (θ_f)	0.30			determined in the laboratory
Moisture content at wilting point (θ_p)	0.131			determined in laboratory
Initial profile moisture content (mm)	15			determined in the field
Upper limit of stage 1 cumulative Evaporation, U (mm)	19	20	20	obtained after calibration for bare, partial and solid cover treatments respectively
α (a parameter depending on hydraulic properties of the soil) (mmday ^{-1/2})	4.5	2.2	0.5	obtained after calibration for bare, partial and solid cover treatments respectively
Drainage constant (τ)	0.27			estimated from soil properties using equation 5.1
SCS curve number (CN2)	0			assigned (no runoff was allowed)

The U and α values arrived at are different from those obtained by van Bavel et al. (1968). They obtained 12 mm and 5.08 mmday^{-1/2} for U and α respectively, for the bare Adelanto clay loam soil as reported in Ritchie (1972).

A plot of simulated against measured moisture content for the three treatments shows the extent to which the model predicts the soil moisture content (figure 5.3). The relationship between the measured and simulated moisture contents is quite good especially for the bare treatment. The coefficients of determination (R^2) for the bare soil treatment, partial cover treatment and solid cover treatment were 0.96, 0.88 and 0.76 respectively.

When the data for all treatments were combined and a graph of measured versus predicted moisture contents were plotted (figure 5.4*), the R^2 was 0.90. For the validation the result is similar to that of the calibration. An R^2 value of 0.89 was obtained. The coefficient of efficiency (as defined by equation 4.16 in chapter four) for calibration and validation were 0.86 and 0.89 respectively (table 5.3).

1

*data for this plot were for six depths on six different dates.

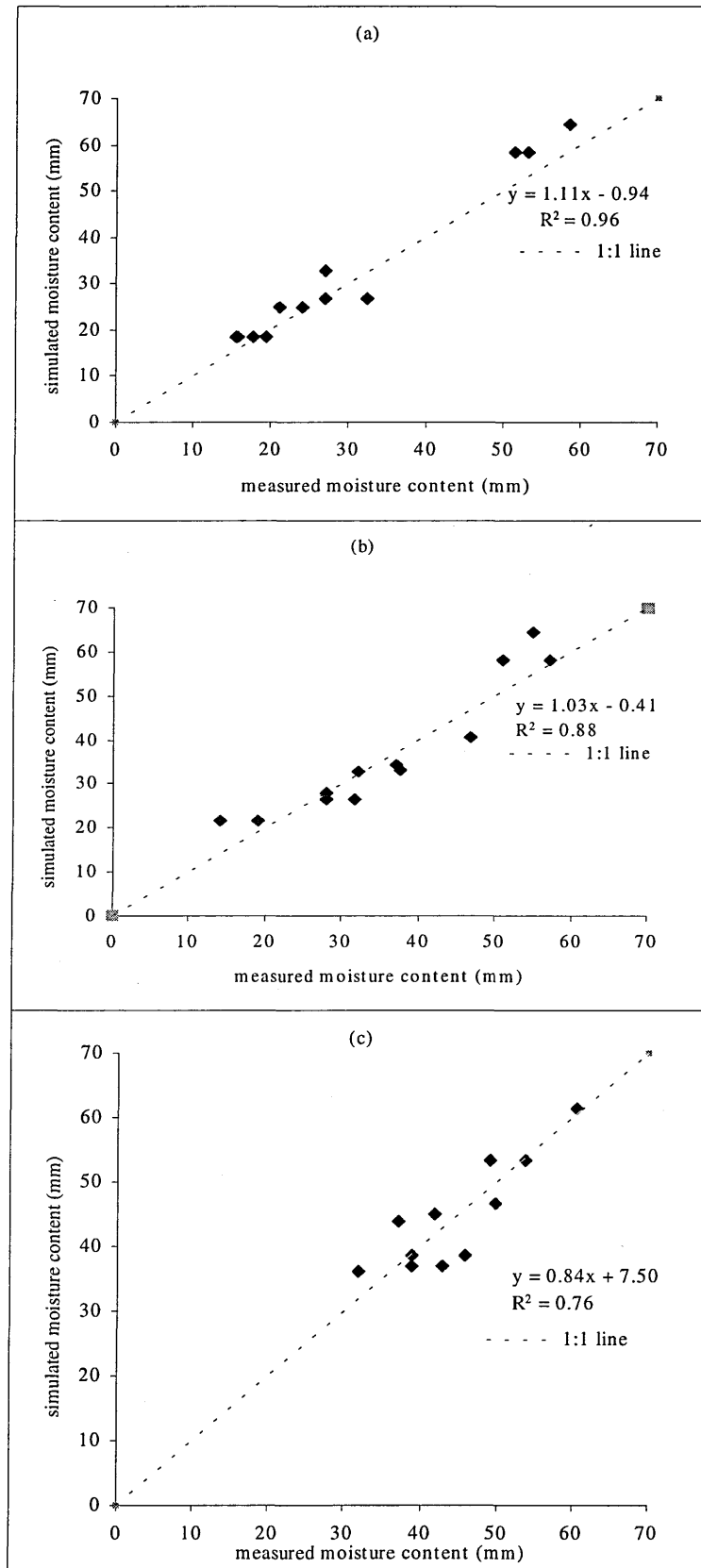


Fig. 5.3: Measured-simulated graphs for (a) bare, (b) partial cover and (c) solid cover.

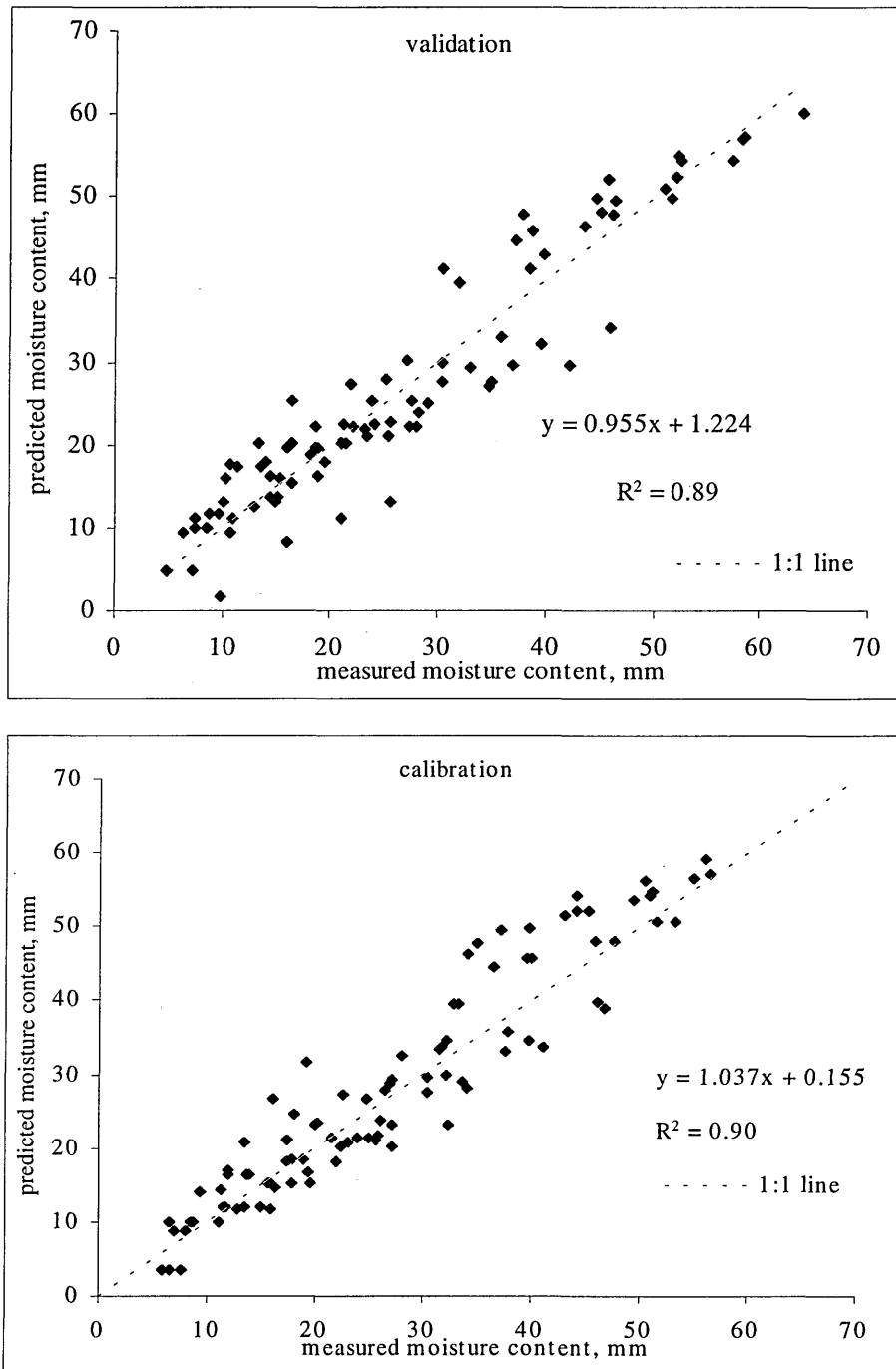


Figure 5.4: Measured versus simulated moisture content plots on different dates (at six depths) for all treatments.

Table 5.3: Evaluation statistics for calibration and validation for both Jawa
and Zurkaya sites

Statistic	Calibration	Validation
R^2	0.90	0.89
E	0.86	0.89

The model simulates the profile moisture content better in bare soil than when the soil surface is covered. This is not unconnected with the fact that, the equation used in BALANCE for simulating evaporation from the soil was derived empirically from uncovered soils (Ritchie, 1972).

It was observed during calibration that the model responds to the calibration parameters mostly during the first few weeks of simulation period. This is because most of the water loss in the model takes place during the first stage of evaporation (Ritchie, 1972).

Field observations revealed that the soil moisture continued to dry up to the end of the experimental period. The drying period (defined here as the time from the start of the experiment to time when the soil moisture remains constant) predicted by the model was however, shorter than the field situation. The parameter α is responsible for the short drying period because it controls the rate at which moisture is transferred from the profile to the evaporating surface. Values of U obtained in the calibration for bare and covered treatments were unexpectedly similar. This may be due to the wide space of time between the first two measurements of the field moisture content, which might have given rise to lack of rapid assessment of changes in the soil water profile especially during the first 3 days. The lower value of α in the covered treatments allowed longer drying period and hence closer reflection of the field condition. The lower the α value the slower is moisture transfer from below the surface to the evaporating zone and the longer the drying period.

5.4.5 Summary of calibration and validation

The Ritchie equation in BALANCE was calibrated and validated on soil moisture content of *fako* areas of northeast arid zone of Nigeria. Calibration was achieved by using the parameters that define the soil evaporation in the model. These parameters were U and α and their values obtained after calibration were respectively 19 mm and $4.5 \text{ mmday}^{-0.5}$ for the bare treatment, 20 mm and $2.2 \text{ mmday}^{-0.5}$ for partial treatment and 20 mm and $0.5 \text{ mmday}^{-0.5}$ for solid treatment. A plot of measured moisture content versus simulated moisture content gave coefficient of determination and coefficient of efficiency of 0.9 & 0.86 and 0.89 & 0.89 in calibration and validation respectively. It was also found out that the BALANCE model predicts shorter drying cycle for the *fako* areas of the northeast arid zone of Nigeria.

5.5 GENERAL CONCLUSION ON BALANCE MODEL

Evaluation of different components of water balance is a necessary pre-requisite to maximise water use by plants and minimise losses due to evaporation and runoff. With accurate estimates of the soil hydraulic parameters and good calibration, the BALANCE model can adequately simulate the water balance components on the *fako* areas of the northeast arid region of Nigeria. The best simulation results were obtained for bare uncovered soils. The model therefore, can be applied to water balance studies on the *fako* areas.

CHAPTER SIX

DEVELOPMENT OF AN EMPIRICAL RAINFALL-RUNOFF MODEL

6.1 INTRODUCTION

For runoff to occur on a catchment, precipitation must satisfy the demands of evaporation, infiltration, depression storage, and interception and channel detention. In arid and semi-arid regions, the predominant runoff mechanism is Hortonian (Dawdy 1991). The nature of the rains is that of short duration storms and therefore loss due to evaporation during the storm is negligible. Also, due to lack of vegetation on the *fakos* there are no interception and transpiration losses. Therefore, storm on the *fako* lands is partitioned into infiltration, surface detention and runoff.

Models can be used to estimate runoff on the *fako* lands. The model to be used will depend upon the available information, the required accuracy and the resolution of the output and the time resources that can be directed at the modelling exercise.

The increasing availability of distributed rainfall and computational resources is providing the opportunity in the developed countries to use distributed models for rainfall-runoff studies and other applications. The distributed models are usually process-based or a combination of process-based and empirical relationships. KINEROS (Woolhiser et al., 1990) and SHE (Abbott, 1986) are examples of process-based models used in the USA and Europe respectively. Both models use fine time intervals and include detailed representation of catchment hydrological processes using algorithms based on physical laws of science. They route the excess rainfall over the catchment by simultaneously solving the equations of continuity and a discharge equation for predicting the movement of runoff within the catchment and eventually to the outlet. Process-based models have both predictive capability and explanation of the processes in the system. Owing to difficulties generally associated with estimating their parameters, they have been of limited value in practical applications (Maheshwari, 1994).

The opportunity of using distributed models is very limited in the developing countries due to a dearth of data and lack of resources. While empirical models embody no scientific theories and do not explain the operative processes, they have predictive capability. Within the range of data analysed, the empirical models may be successful depending on the experience. They depend upon establishing a statistical correspondence between input and output and include a number of successful approaches such as unit hydrograph (Sherman, 1932), extreme frequency analysis and regression analysis (Diskin, et al., 1973). In their study of rainfall-runoff modelling approaches, Chiew et al. (1993) compared six rainfall-runoff modelling approaches ranging from simple polynomial equation to complex conceptual model. They concluded that the simple models are easy to apply and the complex conceptual model is the most difficult to use. However, the complex model provides the best simulation of the daily flows compared to other approaches.

Estimates of the proportion of rainfall that runs off as a function of rainfall amount and soil properties are useful for many purposes. Some of the uses include estimation of water available to crops, catchment yield and soil loss due to erosion. Rainfall data available in the north east arid zone are mostly 24-hour totals and therefore lack the resolution needed for accurate estimates of runoff by process-based models. Existing simple procedures for daily estimation of runoff do not include consideration of variation of rainfall intensity. The soil conservation curve number (USDA, 1972) is a widely used method for estimating runoff from total daily rainfall using soil conditions but does not consider intensity of the rain.

The objectives in this chapter were:

1. to analyse the rainfall characteristic of this area using high resolution rainfall data
2. to develop a rainfall-runoff model suitable for water harvesting in semi-arid North East Nigeria
3. to compare the model developed with the curve number model.

6.2 METHODOLOGY

6.2.1 Rainfall

Data acquisition

The rainfall data used for the development of the runoff model consists of very fine resolution (1 minute or less) record for 13 site-years collected between 1992 and 1994 from seven stations (appendix F). The data were recorded from two types of automatic raingauges. The raingauges were the SKYE type (Skye Instruments) and the DIDCOT type (Didcot Instruments). Accompanied software with these raingauges enables logger configuration, data retrieval, display and manipulation to be carried out. Number of tips of the bucket per period were recorded in 'event' mode and then downloaded and stored in a format importable into spreadsheet. The bucket capacity of the SKYE raingauge is 0.2mm and its time resolution is 30 seconds. The DIDCOT raingauge has a tip capacity of 0.1mm and time resolution of one minute. These levels of resolutions can provide very accurate temporal distribution of the rainfall.

Rainfall data for Jawa, Zurkaya and Garin Alkali (for 1994) stations were collected using the SKYE rain gauge¹ and the rest of the data for Dagaceri, Tumbau, Kaska and Fuchimiram stations were obtained with DIDCOT rain gauge² (see table 6.1).

1- The data for these stations was collected by the author.

2 -The data collected using DIDCOT was obtained from Professor Michael Mortimore, then of Cambridge University and now at African Drylands Research.

Table 6.1: Annual rainfall amount and number of events per year in the 13 site-year period used

Station	Location	Year	Annual rainfall amount (mm)	Number of rainfall events	Raingauge type
Dagaceri	12.86°N, 10.20°E	1992	331.5	53	DIDCOT
Dagaceri		1993	381.7	51	DIDCOT
Dagaceri		1994	402.6	59	DIDCOT
Futchimiram	12.61°N, 12.76°E	1992	311.0	46	DIDCOT
Futchimiram		1994	382.9	57	DIDCOT
Garin Alkali		1993	402.3	38	DIDCOT
Garin Alkali		1994	438.2	55	SKYE
Jawa	12.81°N, 11.04°E	1994	462.0	50	SKYE
Kaska	13.24°N, 10.87°E	1992	257.7	42	DIDCOT
Kaska		1993	296.1	40	DIDCOT
Kaska		1994	435.6	50	DIDCOT
Tumbau	12.00°N, 08.65°E	1992	664.1	55	DIDCOT
Zurkaya	12.82°N, 11.09°E),	1994	548.2	49	SKYE
		Mean	408.8	49	
		Standard deviation	108.6	7	

A 30-year low-resolution data for daily rainfall was obtained from Nguru station. The data was analysed in terms of its yearly distribution and number of raindays per year and compared with the high-resolution data.

Rainfall intensity

Rainfall intensity is one of the most important variables controlling runoff (Wilks, 1989). This is especially so in the tropical areas where rainfall intensity is high and very variable both temporally and spatially (Kowal and Kassam, 1970). It is often necessary to specify temporal pattern associated with rainfall depths for design applications. Attempts were made by various researchers to specify the temporal pattern of design rainfall depths (e.g. Pilgrim and Cordery, 1975; Wilks, 1989; Lough, 1993; Yu and Neil, 1993).

In runoff modelling, accurate results of runoff can be obtained with a high level of characterization of rainfall and detailed soils information. Soil characterization for the uncultivated and denuded *fako* lands was carried out as described in chapter three and is assumed to remain constant for some time. Therefore, variation in surface runoff can be attributed to the variation in rainfall amount and intensity. It is against this background that the distribution of intensity in the 13 site-years was investigated.

Depending on the type of project, the resolution of intensity required will range from as coarse as the annual average to as fine as the maximum 15-minute intensity (I_{15}) or less. Usually, for fine resolution intensity required for critical water management projects and erosion studies, the maximum 30-minute intensity (I_{30}) is adopted. This is the maximum rainfall depth obtained in any 30 minutes of an event, and is usually expressed in mm/h. Characterization of the nature of rainfall intensity would seem therefore to be of central importance to predicting runoff amounts on the basis of daily rainfall accumulations. The 13 site-year high-resolution rainfall data was used for the analysis.

Average daily storm intensity and I_{30} were analyzed in this study. The daily storm intensities were calculated from one or more rainfall events in a day. Raingauge data were summed up into accumulated rainfall to give an increasing function of time.

Summation of the raw data into individual rainfall events was based on two parameters given below:

- 1) magnitude: the minimum size of an event was set at 0.5mm. This was chosen because rainfall events of less than this value is considered trace and has few tips (data points)
- 2) time: the maximum time between tips tolerated before initiating a new event was set at 10 minutes (Sadler and Busscher, 1989).

Daily storm intensity (D_i) was calculated as given by equation 6.1.

$$D_i = R_t/T_t \quad (6.1)$$

Where,

R_t = total amount of rainfall received in a day (mm)

T_t = total time taken during actual rainfall (h)

The average daily storm intensity in a month or a year was calculated by:

$$AD_i = \Sigma D_i/N \quad (6.2)$$

Where,

AD_i = average daily storm intensity (mm/h)

N = number of storms in a month or year

The 30-minute period within an event that has the maximum depth of rainfall was used to calculate the I_{30} for that event. The I_{30} investigation was only possible with events that lasted for at least 30 minutes.

6.2.2 Rainfall-runoff model

To develop a regression relationship between rainfall and runoff for an area, a number of years of rainfall within the area should be considered. Within the limits of time and resources available, it was practically difficult to obtain sufficient natural rainfall-runoff events for the regression analysis. The use of models to simulate rainfall-runoff process for several years over a wide variety of conditions can be employed (Diskin et al., 1973; Boers et al., 1986; Gan and Burges, 1990; Wang and Yu, 1990). In this procedure, the validated processed-based EUROSEM model (Morgan et al., 1992) (see chapter IV) was employed to partition the fine resolution rainfall into infiltration, surface detention and runoff on the *fako* lands.

To be on the same time-scale as that available for the area, the high-resolution rainfall data were partitioned into daily storms (24-hour totals). Results from initial simulations with EUROSEM indicated that, those daily storms of magnitude less than 10mm are unlikely to produce runoff, and were therefore not considered. A total of 165 daily storms were obtained as a result.

Daily rainfall files for EUROSEM simulations were therefore created. Each file constitutes a time-depth distribution of the daily rain to describe the storm by defining the time of the start of each period of the storm and the cumulative rainfall received in the storm up to that time. The minimum time interval between consecutive pairs is one minute. For periods within which the rainfall is fairly uniform in intensity, single pairs were used to represent them.

Corresponding catchment parameter files were also created for the model. A single slope plane with a length of 50m represented the catchment. For each of the storms considered, the value of the total computational time for which the model was run was set at one minute less than the end-time of the last time-depth pair in the rainfall data file. This is to contain the hydrograph of the surface runoff. The option in the model that calls only the hydrological calculations was chosen. Under the 'element wise information' sub-heading of the parameter files, the measured and calibrated values of the parameters (chapter IV) were used.

The volumetric moisture content of the soil at the start of the storm (THI) is one of the sensitive parameters in EUROSEM as far as runoff is concerned (see chapter IV). This parameter controls initial moisture abstraction in the model as it is in other kinematics wave-based models such as HEC-1 (Hydrologic Engineering Centre, 1990) and KINEROS (Woolhiser et al., 1990). Measurements of the THI at the start of each storm were not available, and therefore, a reliable way of estimating THI was necessary to obtain reasonable simulations from EUROSEM.

Three values for THI of the top few centimetres of the soil were used. The values were for initial conditions of dry, average and wet moisture contents. It was observed during the field experimental trials (see chapter III) that the top 10cm of the *fako* soils can dry to as low as 0.02 volume water fraction. The moisture contents at field capacity and at permanent wilting point as determined in the laboratory were 0.30 and 0.13 respectively. A value of 0.075 volume water fraction for the dry initial condition was taken. This is the moisture content value midway between permanent wilting point and the minimum possible. For the average initial moisture condition, a value of 0.205 was used. This is the value midway between moisture content at field capacity and permanent wilting point. Finally, a value of 0.32 representing midpoint between saturation and field capacity was chosen as the initial wet condition.

EUROSEM was then run to predict the depth of runoff generated on a typical *fako* land with each of the 3 initial conditions for all the storms. The predicted depths of runoff from the daily storms were regressed against the daily storms to obtain a linear model of the form given by equation 6.3 (Diskin, 1970; Boers, 1994).

$$\begin{aligned} R &= m(P - C) && \text{for } P > C, \text{ and} \\ R &= 0 && \text{for } 0 \leq P \leq C \end{aligned} \quad (6.3)$$

where;

R = runoff depth [mm]

m = runoff coefficient	[-]
P = rainfall depth	[mm]
C = threshold value depth	[mm]

Microsoft Excel Solver was used to optimize the values of the runoff coefficient and the threshold value by minimizing the sum of the squared residuals.

After development of the model, it was then compared with uncalibrated curve number model (USDA, 1972) given by equation 6.4. The runoffs predicted by both models for the three initial conditions were compared.

$$R = \frac{(P - 0.2S)^2}{(P + 0.2S)} \quad (6.4)$$

Where, $S = \frac{25400}{CN} - 254$

R = runoff (mm)

P = rainfall (mm)

S = maximum storage (mm)

CN = curve number; dependent on the soil condition

To estimate runoff by the curve number method, CN values for the soil of the area should be obtained. These values were obtained from tables (ASCE, 1996). The uncalibrated CN values for the C hydrologic soil group for this area were 83, 85 and 90 for the chosen three initial conditions of dry, average and wet respectively. The prediction of EUROSEM model was used as reference for comparing the two models.

The linear model was then evaluated using the root mean squared error (RMSE) (equation 6.5) about the least squares line.

$$RMSE = \sqrt{\left(\frac{1}{n}\right) \sum (x - y)^2} \quad (6.5)$$

where;

n = number of observations

x = EUROSEM prediction

y = Linear model prediction

6.3 RESULTS

6.3.1 Rainfall

Distribution

Figure 6.1 shows the distribution of the rainfall used in the model development. The number of stations used had increased the scale of time from 3 to 13 years (Boers, 1994). Considering the end use of the analysis, this period is sufficient to represent the range of rainfall data expected in this area for it to be used in microcatchment water harvesting design.

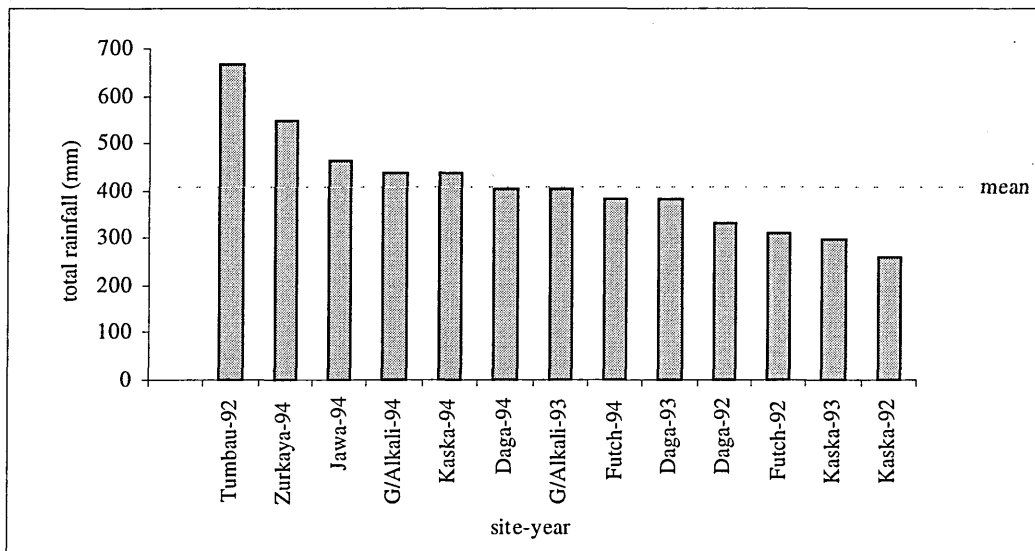


Figure 6.1: Annual distribution of rainfall for 13 site-years.

The mean annual rainfall for the 13 site-years was 408.8mm and the standard deviation was 108.6mm (table 6.1). This mean is close to the 30-year (1961-1990) mean for Nguru station (435mm), but higher than the 338.2mm mean for the last decade (1981-1991). The 1981-1991 decade was the driest amongst the last three decades (Hess, 1996).

More than 95 % of the storms greater 10mm were recorded in the months of July, August and September, with only about 2% each in June and October. Number of rainfall events (based on the two parameters defined earlier) per year for the period used in this analysis is slightly different from the number of raindays for the 1961-1990 period. The average number of events per annum for the 13 site-years was 49 (table 6.1) while the number of raindays for Nguru station for 1961-1990 period was 36. The maximum and minimum numbers were 59 and 38 respectively for the data used, and for the 1961-1990 the maximum number of raindays was 46 and the minimum was 20. The standard deviations were 7 and 8 events respectively. Average dry spell, defined as the average number of dry days between raindays, calculated for the 13 site-years was 3 days. This is the same with that for the period 1961-1990.

Generally, the annual distribution of the 13 site-year rainfall is sufficiently representative considering its similarity with the data of 1961-1990 period and therefore, can be used to represent a long period (1961-1994) record for the area.

Intensity

Table 6.2 shows some characteristics of the daily storm intensities in each month during the rainy season.

Table 6.2: Characteristics of daily storm intensities (mmh^{-1}) in each month of the rainy season.

	June	July	August	September	October
Average intensity	34.28	23.61	21.71	22.30	16.32
Maximum	40.88	55.68	84.19	40.76	20.66
Minimum	26.30	4.45	5.95	6.62	9.01
<i>Count</i>	4	45	82	29	5

The distribution of the daily storm intensity indicates that the storms were higher in intensity during the early stages of the rainy season. In June the average storm intensity was 34.28 mm/h compared to 16.32 mm/h in October. However, the maximum and minimum of 84.19 mm/h and 4.45 mm/h were recorded in August and July respectively.

Table 6.3 compares the result of both the daily storm intensity and the I_{30} for all the 13 site-years. The average storm intensity over the whole 13 site-years was 22.47 mm/h and its standard deviation of 12.17 mm/h. For I_{30} , the mean for the 13 site-years was 53.9 mm/hr and the standard deviation was 24.24 mm/hr.

Table 6.3: Characteristics of daily storm intensity and I_{30} for the entire 13 site-years (mm/h)

	Daily intensity	I_{30}
Average	22.47	53.9
Maximum	84.19	160.4
Minimum	4.45	25.8
Standard deviation	12.17	24.24

Coefficient of variation of the storm intensity over the 13 site-years is about 54% and it is nearly the same with that of the I_{30} . The overall result of the intensity analysis indicates that this characteristic of the rain is variable even with as coarse a data as the daily storm intensity. It was also observed that both the daily storm intensity and the I_{30} were higher during the beginning of the rainy season.

6.3.2 Rainfall-runoff model

The Threshold value

The least squared line fitted through the 165 data points of rainfall and runoff gave threshold values of 16mm, 13.6mm and 10mm for the dry, average and wet initial conditions respectively. The drier the assumed soil initial condition, the closer is the prediction of the linear model to that of the EUROSEM model. The dry initial condition gave the least root mean squared error of 3.49mm. Figure 6.2 shows the plot with a dry initial condition.

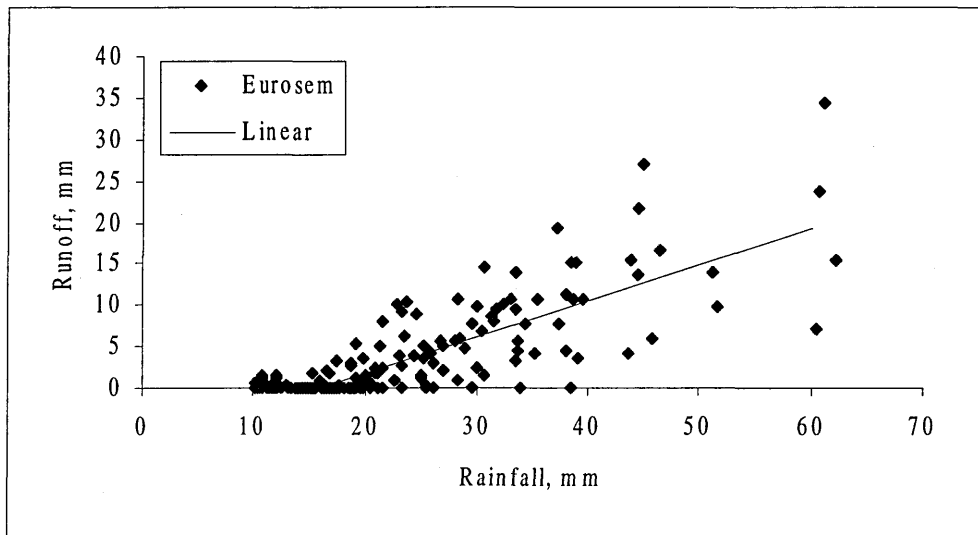


Figure 6.2: Relationship of rainfall and runoff for the EUROSEM and Linear model for dry initial condition.

The threshold value accounts for the initial amount of water the soil absorbs plus the detention storage if any. When the initial condition was changed from dry to average, the threshold value decreased from 16mm to 13.6mm, and when changed to wet, the threshold value decreased further to 10mm. Compared to the initial abstraction (0.2S) of about 10mm from the curve number method, the 16mm threshold value for the dry initial condition is high. On the contrary, Duru and Hjelmfelt (1994) reported that on the Ida and Monona silt loam soils under dry conditions, the HEC-1 model (Hydrologic Engineering Centre, 1990) predicted that up to 26mm of rainfall goes into abstraction before runoff starts. Boers (1994) used a value of 6mm in his prediction from Niamey data.

The assumption of an initial dry condition is reasonable considering the 3-day average dry spell and the quick rate at which the soil dries out. In 3 days without rain, the top few centimetres of the soil in this region can dry to the 0.075 value assumed.

The runoff coefficient

Runoff coefficient takes account of the soil infiltration rate and the rainfall rate. The model assumes an average daily intensity for the rainfalls of the region. The runoff coefficients obtained for the dry, average and wet initial conditions were 0.44, 0.49 and 0.58 respectively. This means that the drier the soil, the higher the initial absorption capacity of the soil and hence lower runoff coefficient value. Diskin (1970) reported values for different areas in the USA ranging from 0.37 to 0.99. Considering the low infiltration of the soil (1 mm/h) he used and the high intensity nature of tropical storms, value of 0.25 for runoff coefficient assumed for predictions from Niamey data by Boers (1994) was rather low.

Comparing the linear model with curve number model

The graph of rainfall versus runoff predicted by EUROSEM, linear and curve number models is shown in figure 6.3. This is the plot with an initial dry soil condition. The plot shows that the linear model and the uncalibrated curve number model give similar predictions of runoff especially with storms of magnitude less than 45mm.

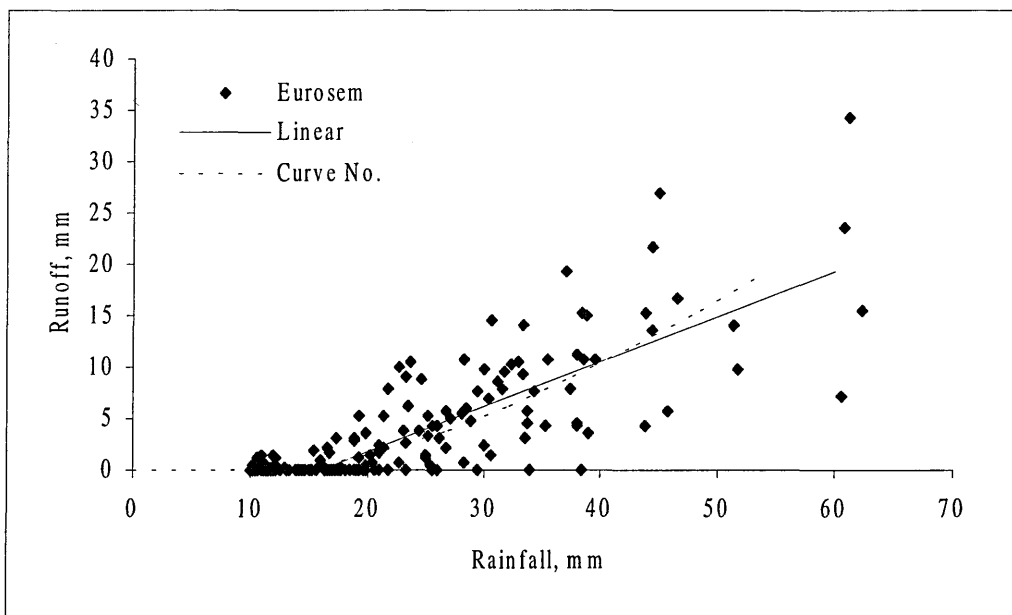


Figure 6.3: Comparison of linear and curve number (CN from table) models.

The root mean square error between predictions of the EUROSEM model and those of the linear and curve number models are presented in table 6.4. The errors were highest with both models (linear and curve number) when wet initial condition was used. Predictions of both models were closest to that of the EUROSEM model with an initial dry soil condition. The root mean squared errors calculated for the two models were respectively 3.49mm and 3.61mm and therefore, runoff prediction by the linear model is slightly better than that by the curve number model.

Table 6.4: Root mean square errors (RMSE) of predicted runoff by linear and curve number models as compared on EUROSEM model.

Initial condition	Linear model (mm)	Curve number model (mm)
Dry	3.49	3.61
Average	3.73	3.95
Wet	4.3	4.65

6.4 GENERAL DISCUSSION

Many advances have been made over the years in the development of discrete input-output models for the rainfall-runoff process (Diskin, 1970; Wang and Yu, 1990). A linear regression of rainfall and runoff, similar to the ones proposed by Diskin (1970) was performed to obtain a linear rainfall-runoff model for the *fako* areas. The model attempts to establish a relationship between rainfall and the resulting runoff for a given catchment area. The purpose of the model is to be used for prediction of runoff on the soil surfaces of *fako* lands for microcatchment water harvesting designs.

The success or failure of rainwater harvesting depends largely on the quantity of water that can be harvested from an area under given climatic conditions. The quantity of water is dependent on the runoff efficiency of the area.

As earlier mentioned, runoff volume depends on such components as the rainfall intensity, soil infiltration capacity and surface storage. All the three components can be taken into consideration, to a certain extent, by measuring the runoffs resulting on the surface from various rainfall regimes.

6.4.1 Predictions by the EUROSEM model

It can be seen that the general trend of the rainfall-runoff relation is such that runoff increases as the rainfall size increases. However, the estimated runoffs from 34 out of the 165 storms simulated by EUROSEM model exhibited inconsistent tendencies as regards the general trend of the rainfall-runoff relationship. These inconsistencies may be ascribed to the nature of the intensities of the storms. At one end of the scale are storms with very low intensities and at the other end are storms with very high intensities.

Of the 165 storms simulated by EUROSEM model, 51 or 31% did not produce runoff, out of which 23 were of magnitude greater than the threshold value. The 23 storms for which EUROSEM predicted no runoff (although their magnitudes were higher than the threshold value), was due to the fact that the intensities of the storms were low compared to the absorption capacity of the soil during those times. For example, in spite of size (38.4mm) EUROSEM predicted no runoff for the rainfall of 03/08/94 for Jawa. This rain fell in over 20 hours with an I_{15} of about 42 mm/hr that was recorded in the first 15 minutes of the start of the rain (figure 6.4). During the rest of the storm period, the intensity was far lower, and in particular the intensity was nearly zero between the third and twelfth hours of the storm.

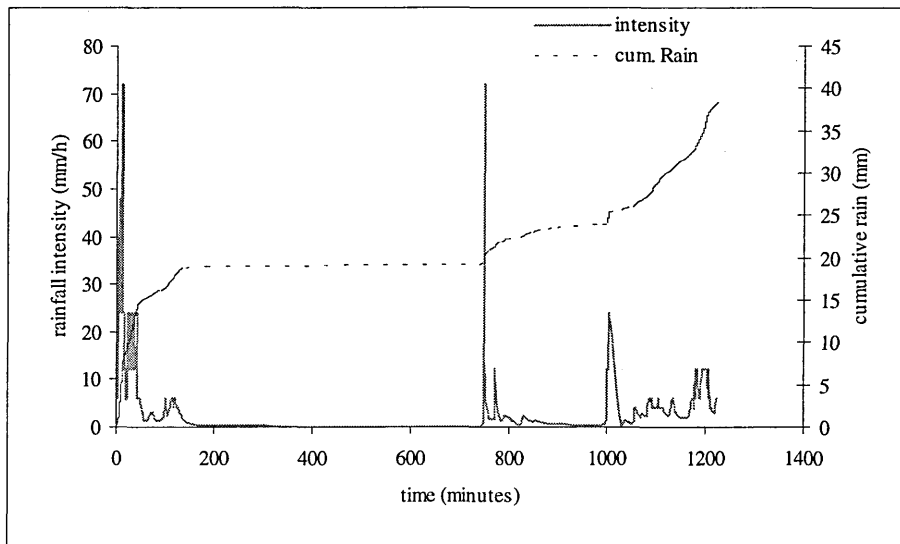


Figure 6.4: Distribution of intensity during the storm event for Jawa on 03/08/94.

On the other hand, 49 or 30% of all the storms were less than the 16mm threshold value, out of which 10 storms were predicted by EUROSEM to have produced runoffs. The reason for such low magnitude but runoff-yielding storms is that their high instantaneous intensities leave very little opportunity for infiltration. The rainfall of Kaska on the 01/09/94 is an example of such storms. The total depth of the storm was 10.7mm and it was recorded in 25 minutes. About 85 % of the storm fell in just 8 minutes within which the intensity reached a peak of 120 mm/h for about 2 minutes (figure 6.5). The rainfall rate during that time far exceeded the infiltration capacity of the soil.

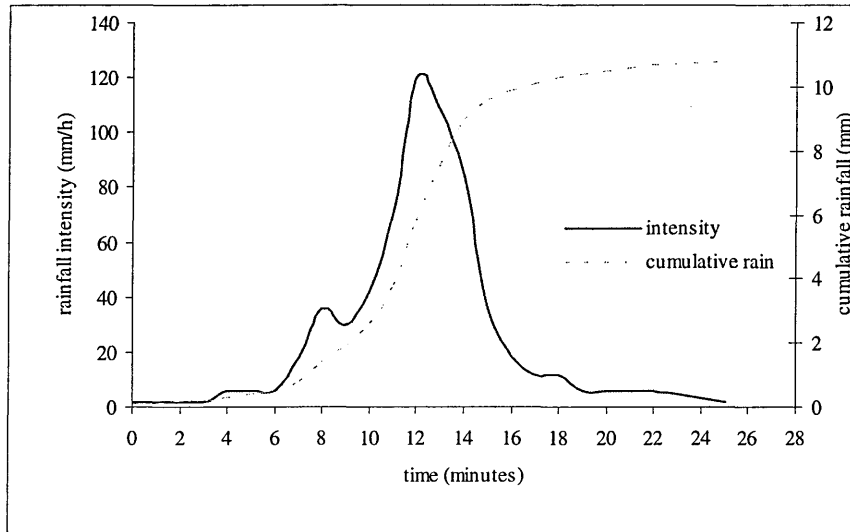


Figure 6.5: Distribution of intensity during the storm of 01/09/94 for Kaska station.

Despite the runoff generating capabilities of such high intense but small storms, the total runoff resulting from them are usually small because of their size. Of the 10 small storms that the EUROSEM model predicted runoff from, only one generated 2mm of runoff, four generated between 1mm and 2mm of runoff and five yielded less than 1mm of runoff. Therefore, the value of 16 mm obtained for the threshold value was realistic.

6.4.2 Predictions by the Linear model

The linear model predicted that 11 storms (6.7 % of the total number of storms) generated runoffs of magnitude outside the 95% confidence interval of the model. All the 11 storms had intensities outside the 95% confidence interval as far as the data for the period used for the study is concerned.

The storms of 11/09/94 for Dagaceri and that of 03/08/94 for Jawa again are examples for the two opposite ends respectively. The EUROSEM model predicted 10mm of runoff as a result of the 22.8mm storm for Dagacheri, while the linear model estimated only 3mm of runoff. This can be explained by the distribution of the rainfall during the storm. Ninety four per cent of the Dagacheri rain was recorded in 45 minutes with an I_{15} of 72 mm/hr reaching a peak of 106.5 mm/hr for 4 minutes.

EUROSEM responded well to the high intensity rain, but for the linear model this was outside its scope and therefore, underestimated the runoff by about 70 per cent. For the other example, the linear model predicted 9.8mm of runoff because of the 38.4mm Jawa storm, while EUROSEM predicted no runoff due to the low intensity of this high amount of rainfall.

6.4.3 Monthly distribution of runoff predicted by EUROSEM and linear models

The total monthly distribution of rainfall and their corresponding runoffs for the entire 13 site-years as predicted by EUROSEM, linear and curve number models are given in table 6.5. Proportionate to the monthly amounts of rainfall, the runoffs were mostly in the months of July, August and September as predicted by all the models. The values range from 0.5mm for October to 345.9mm for August from EUROSEM model, 4.3mm for October to 350.1mm for August from the linear model and 4.4mm for October to 332.8mm for August from the curve number model.

Table 6.5: Monthly distribution of rainfall and runoff as predicted by EUROSEM, linear and curve number models.

Month	Rainfall amount (mm)	Runoff (mm)		
		EUROSEM	Linear	Curve number
June	82.9	15.0	11.7	9.9
July	1046.8	187.1	158.7	151.5
August	2019.1	345.9	350.1	332.8
September	643.6	89.9	101.3	98.1
October	82.5	0.5	4.3	4.4
Total	3874.9	638.4	626.1	596.7

Both the linear and curve number models under-predicted the runoff for the months of June and July and over-predicted for the month of October. The disparities between the predictions of EUROSEM model and that of the two models again may be explained on the basis of storm intensity variations. Unlike EUROSEM, the linear and curve number models are not process-based models. The high and low storm intensities observed for the early and late rains respectively, were reflected in the predictions of EUROSEM model, whereas the linear model assumes average storm intensity for the entire season and the curve number model takes no consideration of intensity. Predictions by all the models were similar for the months of August and September. The intensity of the storms in the months of August and September were generally near the average for the entire season and therefore, the runoff predictions by the two models were close to that by EUROSEM model.

Total runoff predicted by the linear model over the whole season (626.1mm) is close to that predicted by the EUROSEM model (638.4mm). This is because the average intensity assumed in the linear model evened out the disparities of the early and late months.

Both the linear and Curve number models are conceptual approximations based on historical data but do not have physical basis for the relationships used. Both models give similar results with little difference in the RMSE and runoff efficiencies as far as this finding is concerned. In water harvesting for agricultural purposes where average results may be sufficient, the linear model developed and the curve number models are appropriate and very useful. However, some advantages and disadvantages can be found.

The following are some of the advantages of the linear model over the curve number model

1. In addition to the average soil condition, the linear model assumes an average intensity for the daily rainfall of the region based on the rainfall record used in its development.

2. The linear model does not require judgement and experience to use as required by the curve number method to adjust the curve numbers.

Some of the limitations of the linear model include:

1. The model describes average conditions that are useful for design purposes and for application in the region only.
2. If the intensity for a particular storm approaches the extremes, the linear model will grossly under-predict or over-predict the runoff resulting from that storm.
3. It assumes that the initial condition before each rainfall event is dry, thereby allowing a threshold value of 16mm irrespective of when last rainfall had occurred.

6.5 SUMMARY

The rainfall distribution in the northeast arid zone of Nigeria is such that about 95 % of it fall in the months of July, August and September. The mean annual rainfall for 13 site-years is 408.8mm with a standard deviation of 108.8mm. Storm intensity analysis revealed that the rains are higher in intensity at the beginning of the season and lower towards the end of the rainy season. The average storm intensity over the entire rainy season was found to be 22.47 mm/h with a coefficient of variation of about 54 %.

A linear regression model for predicting runoff from daily rainfall was developed for the *fako* lands of northeast arid region of Nigeria. The linear model can be regarded as an integral expression of the physiographic and climatic characteristics that govern the relations between rainfall and runoff on the *fako* areas. Runoff coefficient and threshold value obtained for this area were 0.44 and 16mm respectively. The threshold value obtained in this study is lower than that predicted by the HEC model (Hydrologic Engineering Centre, 1990) under dry conditions on silt loam soils (Duru

and Hjelmfelt, 1994). The linear regression could explain 80 % of the variation. This means that the model can be used for prediction of runoff from rainfall.

Due to variations in intensity during the rainy season, the linear model underestimated runoff at the beginning of the rainy season and over-estimated towards the end of the rainy season. The average runoff efficiency obtained on a typical *fako* land is about 0.16.

Compared to the curve number model for predicting runoff from daily storms, the linear model is as good. The simplicity and ease with which the linear model can be used places it at a slight advantage over the curve number model. However, the linear model can be used only for the *fako* lands of northeast Nigeria from which soil and rainfall data were gathered and used in the development of the model.

CHAPTER SEVEN

APPLICATION OF MODELLING TECHNIQUES TO WATER HARVESTING

7.1 INTRODUCTION

In dryland areas such as the north-east arid zone of Nigeria, losses of water applied to the soil surface by rain or irrigation can deprive crops or other plants of a major portion of the limited water. The losses might be due to runoff, direct evaporation or drainage beyond reach of plant roots. Runoff caused by high intensity rains can be harvested, stored and conserved for later use by the plants.

Trees are used for a variety of purposes in the arid and semiarid region of Nigeria. Some of the uses of trees include source of energy in the form of fuelwood (especially in the villages) and provision of shades to people and livestock. Also, through the establishment of shelterbelts and windbreaks, trees stabilise the soil and offer protection to the land from the vagaries of both wind (Ujah and Adeoye, 1984) and water erosion. For tree-planting programme in the north-east arid zone, the neem (*Azadirachta indica*) tree is used. It is a fast growing and drought resistant tree that is widely used to reforest semiarid areas. It is a very valuable and popular tree. The seedlings of neem tree (six months to one year old) are grown in the nursery and then transplanted on to the degraded lands.

The tree-planting programme initiated by the authorities in Nigeria has shown little results due to inadequate supply of water. Supplementing the water supply through the application of properly designed water harvesting schemes can help towards achieving the goals of the programme. Water harvesting techniques can range in sophistication from the ancient type used in the Negev Desert of Israel more than 4000 years ago to the recent types. In the ancient type, small lower-lying areas of the Negev were cultivated by an irrigation system that collected rainfall from hillside areas and concentrated the runoff by a system of contour ditches (Evanari et. al,

1982;). The recent water harvesting techniques may involve collection and storage of runoff from roofs of houses (Pacey and Cullies, 1986) and from roaded catchments (Cooley, 1975). It also includes carefully designed microcatchments for agriculture which may involve the use of soil treatments to increase runoff (Frasier et. al, 1987).

A microcatchment as defined by Boers (1994) is a small area in the order of a few hundred square metres or less, consisting of a runoff area with a maximum flow distance of 100m and an adjacent basin area with a tree, bush or row crop. The *fako* areas in the North East Arid Zone of Nigeria were found to have high runoff yielding capacity on the surfaces and good water holding capacity in the profile as was reported in chapter 3. Field trial on the *fako* (see annex to this chapter) also shed some light on the potentials of undertaking water harvesting projects.

To apply microcatchment to the tree planting programme in Nigeria, the tree seedlings can be transplanted in the basin area where water from the runoff area is collected and stored in the soil profile to be drawn upon by the plant during the long dry season.

The objectives in this chapter were:

1. to demonstrate the potentials or otherwise of water harvesting on *fako* areas in north east Nigeria, and
2. to recommend appropriate microcatchment size for neem tree growth on the *fako* areas.

To achieve the above objectives, both field and modelling approaches were followed, with the latter dominating. The annex to this chapter describes the preliminary field trial carried out during 1994 rainy season, which due to the positive indication of water harvesting, informed the decision to use models to investigate further. In the modelling approach, a system of models was applied to combine surface runoff and water distribution in the soil profile. The linear model developed in the last chapter was applied to estimate surface runoff resulting from rainfall, and the BALANCE

model (Hess, 1994) was applied to partition the rainfall and run-on into the various water balance components.

7.2 METHODOLOGY

7.2.1 Conceptual model

The water harvesting system conceptualised for the area is as illustrated by figure 7.1. The system consists of a bare, gently sloping runoff area that collects rainfall and supplies it to the basin area in which a tree seedling is planted.

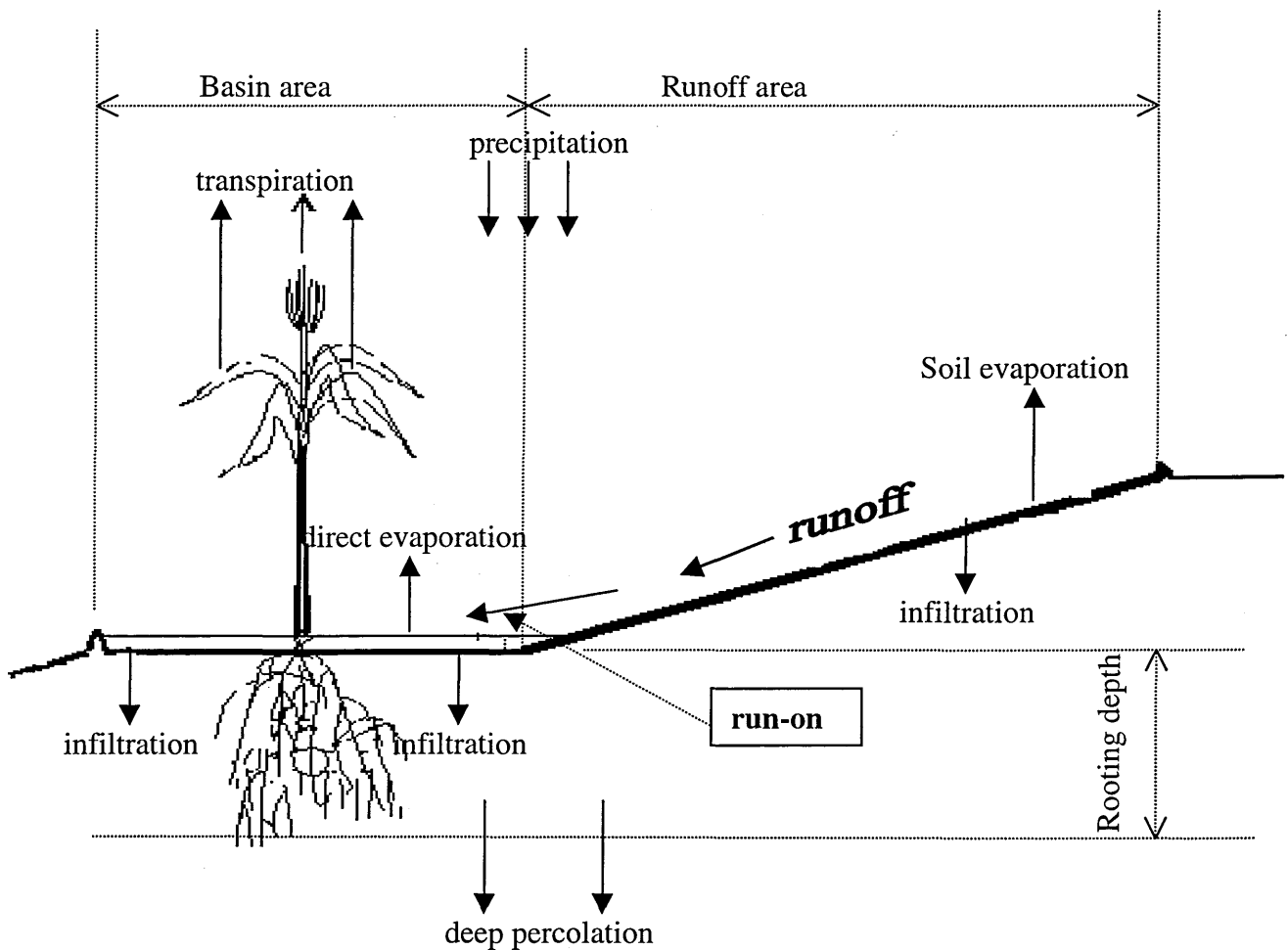


Figure 7.1: Schematic diagram of a micro-catchment showing runoff and basin areas with the various water balance components.

The ideal situation is such that all the runoff will be collected and stored in the soil profile for use during dry period by the plant. This may be achieved with minimum overflow and drainage of water. The linear model (developed in chapter six) was used to estimate the amount of runoff generated on the runoff area. In order to predict quantitatively to what extent the various water balance components were affected by runoff harvesting, it was necessary to evaluate the balance and storage of the soil water. This evaluation was carried out using the BALANCE model (Hess, 1994). To simulate the whole system, the two models have to be linked and therefore, the linear runoff model was integrated into the BALANCE model via its meteorological data file.

7.2.2 Integrating the linear model with the BALANCE model

The linear model estimates the possible depth of runoff (R in mm) that is generated on the runoff area from a rainstorm (P in mm) according to equation 7.1.

If $P > 16$,

$$R = 0.44(P - 16) \text{ (see chapter six)} \quad (7.1)$$

otherwise, $R = 0$

The volume of runoff (V) resulting from the storm P on a runoff area A is

$$V = 0.44(P - 16)A \quad (7.2)$$

This volume of runoff will make a depth of water d in the basin area (B) given by

$$\begin{aligned} d &= 0.44(P - 16)A/B \\ \dots &= 0.44(P - 16)r \end{aligned} \quad (7.3)$$

where,

$$r = A/B, \text{ (the ratio of runoff area to basin area).}$$

While runoff (d) is being collected, the basin area at the same time receives direct rainfall. The total depth (D) of water (flux) in the basin area is therefore,

$$D = P + 0.44(P - 16)r \quad (7.4)$$

The maximum depth of water D allowed in the basin area was 200mm. Equation 7.4 was used to calculate and create a library of meteorological files for different years and different microcatchment sizes (ratios) for the BALANCE model as described below.

7.2.3 Microcatchment water harvesting

Daily rainfall data from a meteorological station at Nguru for 30 years (1961-1990) were used. The 30 hydrological years (1st May to 30th April) were grouped under dry, moderate and wet years. A hydrological year was considered a dry year if the total rainfall received in that year was below 350mm, moderate if the rainfall was between 350mm and 550mm and wet if the total rainfall in that year is more than 550mm. The dry, moderate and wet years defined have probabilities of exceedance of 80%, 50% and 20% respectively.

Each hydrological year had 5 microcatchment size treatments (C, 0, 1, 2 & 3) and two soil cover treatments. The microcatchment size was determined by adjusting rainfall as input to BALANCE, while soil cover treatments were determined by the calibrated cover values of U and α . The basin area was kept constant at 4m² (2m × 2m) and only the runoff area was varied.

The five microcatchment size treatments were:

- 1) Control (C) - this represents the current field condition i.e with runoff but no run-on (44 % of storms greater than 16mm is lost to runoff)
- 2) $r = 0$ - this represents runoff control in which no runoff is allowed in or out of the basin area.
- 3) $r = 1$ - this is the situation where runoff is collected from an adjacent runoff area equal in size to the basin area.
- 4) $r = 2$ - this is the size in which the runoff area is twice the size of the basin area, and
- 5) $r = 3$ - here, the runoff area is three times the basin area.

For the soil cover assessment, the treatments were:

no cover - represented by calibrated U and α values of 19mm and 4.5 respectively for no cover, and

partial cover - represented by calibrated U and α values of 20mm and 2.2 respectively for partial cover.

solid cover - represented by calibrated U and α values of 20mm and 0.5 respectively for solid cover.

For the 30-year period, a total of 150 meteorological files were created. The profile depth was set at 200cm and initial moisture content was set at permanent wilting point value of 0.13 volume water fraction as determined in the laboratory.

A single crop file was created for the neem physiological properties. In this file, transplanting date was set at the first week of July, when the rains must have wetted the top soils and also to take advantage of most of the length of the rainy season. Typical transplanting depth of 25cm was used. Neem tree seedlings can grow roots down to a depth of 150cm in one year provided there is water to that depth

(NEAZDP Staff, personal communications). Consequently, rooting depth was set at 150cm. Crop coefficient (K_c) for neem tree growing in this type of environment was set at 0.7 (Boers 1994).

The model was set to give the results on decadal (10-day) basis. With three soil cover treatments, a total of 450 simulations for the 30 years were carried out. Assessments of the effects of the size and cover treatments were carried out in terms of total storage of soil water and transpiration in each year.

7.2.4 Assessment of Ponding

Ponding would result in the basin area after harvesting the runoff. If prolonged ponding is allowed, there could be two negative effects on the objective. First, some of the harvested water might be lost to direct evaporation, which means reduced amount of water. Secondly, if rains are too frequent, free exchange of gases between plant roots and atmosphere may be restricted and oxygen supply in the soil could be limited and the plant may be stressed and eventually die. It was therefore necessary to evaluate the period of ponding in the basin area.

Using estimates of the important hydrological processes, a spreadsheet was written to evaluate the quantity of water lost to direct evaporation from the ponded basin area and the time taken for a 200mm depth of water to dry out. Figure 7.2 depicts the important hydrological components acting on the ponded water in the basin area as conceptualised in terms of states and rates. The components were the input of rainfall plus run-on, and the output comprising evaporation, infiltration and overflow from the surface storage. Rainfall data of 1994 and infiltrometer measurements for Dumburi, Jawa and Zurkaya areas were used for this investigation. Overflow can result only when the surface storage capacity (200mm) is reached. It was assumed that slope of the basin was zero and evaporation was taking place at its potential rate. Potential evaporation refers to Penman's (1948) definition of the quantity of water evaporated from an extensive free water surface.

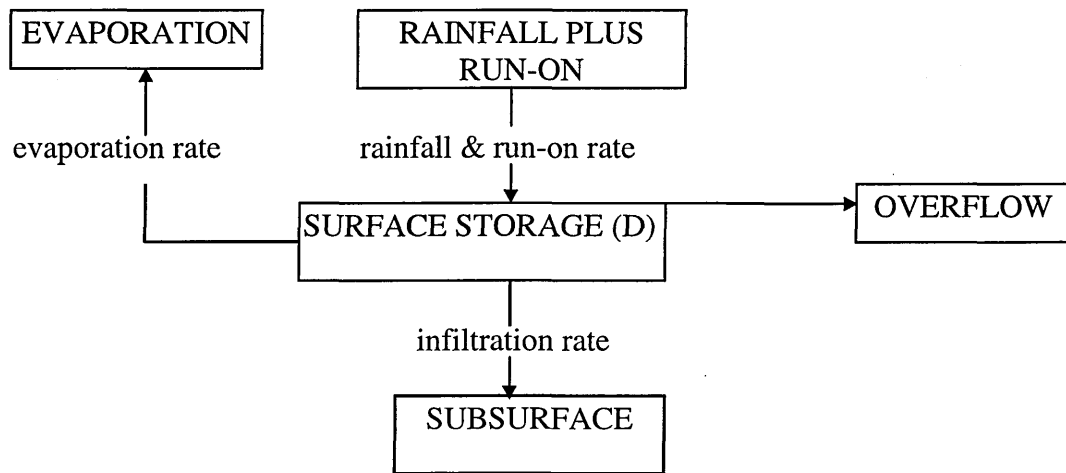


Figure 7.2: Conceptual representation of ponded water showing the different states and rates acting on it.

Final infiltration rates obtained with the double ring infiltrometer (Amerman, 1983; Talsma & Hallam, 1980) for the three sites were used. The infiltration process was substituted with the simplified Kostiaikov (1932) equation (7.5). The Kostiaikov equation is used in describing infiltration under initially flooded condition to obtain the parameters a and n .

$$d_i = at^n \quad (7.5)$$

where,

d_i = cumulative depth of infiltrated water	(mm)
t = cumulative time	(min)
a = empirical constant	(mmmin ⁻ⁿ)
n = empirical parameter	(-)

For the daily evaporation, long-term mean monthly values of between 4 mm/day and 8 mm/day for the area (Hess, 1998) were used.

7.3 RESULTS AND DISCUSSIONS

7.3.1 Distribution of rainfall data used.

Table 7.1 shows the distribution of annual rainfall in the dry, moderate and wet years. Out of the 30 years, 9 can be considered dry, 15 moderate and 6 wet years. The means for these years were 284.7mm, 461.4mm and 594.9mm and their standard deviations were 46.8mm, 49.4mm and 33.8mm respectively. As far as the literature shows, there are only a few assessment of the trends and changes of rainfall characteristics in Nigeria (e.g. Olaniran, 1991, Hess et al., 1995; Tarhule and Woo, 1998).

Table 7.1: Distribution of annual rainfall under dry, moderate and wet years for Nguru station between 1961 and 1990.

	Dry	Moderate	Wet
Range (mm)	<350	350 - 550	>550
Number of years	9	15	6
Mean (mm)	284.7	461.4	594.9
Standard deviation (mm)	46.8	49.4	33.8

The entire rainfall data used gave a good representation of the distribution for the area as reported by various authors. The mean for the moderate years is close to the published mean of 420mm for Gashua (NEAZDP, 1991), a station 50km west of Nguru. Seven out of the 9 dry years were in the 1980s, a dry decade reported in the literature (Nicholson, 1983). The wet years were in the 1960s and 1970s.

Rainfall in the period between August to mid-September is characterised by frequent rains and more amount of rain per rainday. The mean rain per rainday calculated for the dry, moderate and wet years were respectively 13.1mm, 12.6mm and 15.3mm, and their average dry spells were 3.8 days, 3.1 days and 2.7 days (see table 7.2)

Table 7.2: Rainfall characteristics in the period August – mid September for moderate, dry and wet years.

Rainfall characteristic	Dry	Moderate	Wet	Average
Mean rain in Aug-mid Sept	160.4	203.4	271.6	211.8
(mm)				
Mean number of raindays	12.8	15.9	18.2	15.6
Mean rain/rainday in Aug-mid Sept.	13.1	12.6	15.3	13.7
(mm)				
Average dry spell	3.8	3.1	2.7	3.2
(days)				

7.3.2 Microcatchment water harvesting

a) Effect of microcatchment size on soil water storage

Figure 7.3 is a graphical representation of the temporal variation of the total storage in the profile for the five treatments for 1980, a typical dry year. Total rainfall for the year was 339.6mm, and it was received in 31 raindays. According to the definition of

start and end of rains of Sivakumar (1988), the 1980 rain started on May 27th and ended on September 11th. The average dry spell during this period was 3.5 days.

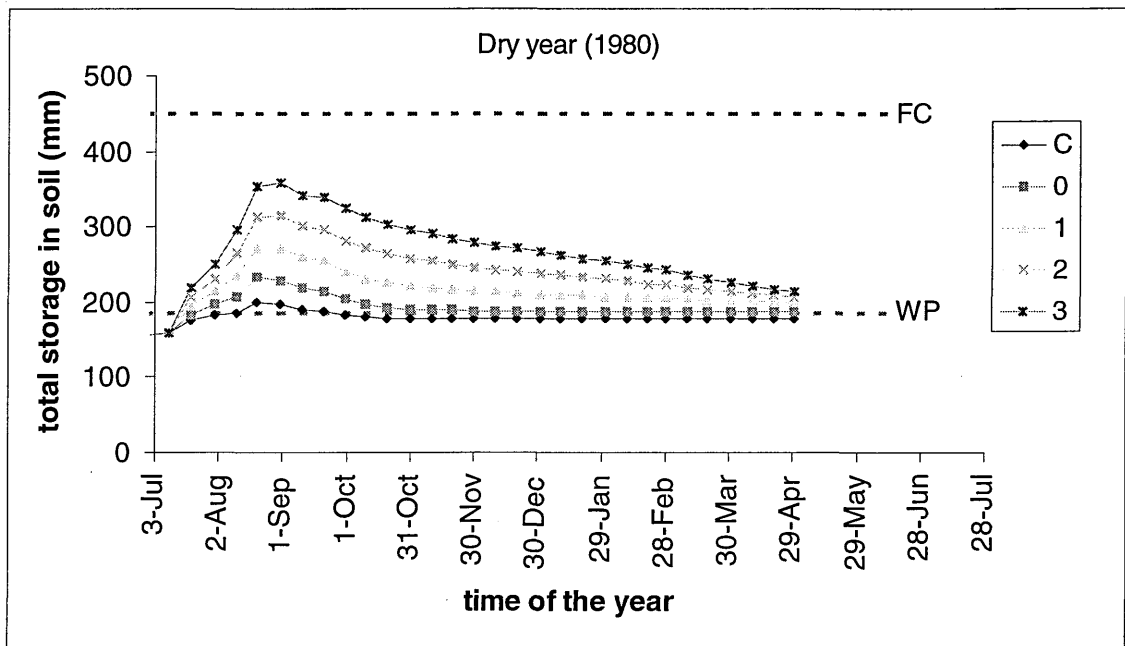


Figure 7.3: Temporal variation of soil water storage for the 5 treatments in a typical dry year (1980). Where FC = field capacity and WP = permanent wilting point.

Results from the simulations shows that the soil available water reached the permanent wilting point value before the end of the hydrological year with treatments C and 0 in all the dry years. This implies that there was not enough moisture in the soil for the seedlings to utilise before the start of the next rainy season as predicted by model. With treatment 1, the model predicted enough water in the soil for uptake by the seedlings in only 2 (1973 & 1988) out of the 9 dry years. For treatments 2 and 3, sufficient water in the soil was predicted by the model in all but 3 years (1972, 1983 & 1986).

It can be said that in dry years, the moisture storage in the soil profile with treatments C, 0 and 1 were just about the critical value of permanent wilting point before the start of the following rainy season. With treatment C, the soil water reached the permanent wilting point level around mid October (soon after the rains). It is assumed that the plant cannot survive beyond October due to water stress with this treatment. By applying treatment 0 (i.e. when runoff was controlled), the soil water was increased to a level sufficient for the plant to utilise for an extra three months. When the treatment was applied, the model predicted that the plant can have enough water to utilise up to the beginning of May the following year. However, the plant can only survive if the rains come early in May. Although the soil water storage with treatments 2 and 3 appeared little, it was still enough for the plant to utilise up to the beginning of the next rainy season.

In an extreme dry year such as 1983, the model predicted that the plant could not have enough water in the soil even with treatment 3. The total rainfall for that year was 234.7mm. There were only 4 runoff producing storms ($> 16\text{mm}$) out of the 20 rain days for that year and water harvesting could not provide sufficient water to sustain growth of the plant in that year.

The soil water behaviour in moderate years was not much different from that of the dry years especially towards the end of the hydrological year (figure 7.4). The slight difference between the moderate and dry years is that, in moderate years, treatment 1 provided just enough soil water for the plant to take it through to the next rainy season as predicted by the model. There was also more stored water in the profile with treatments 1, 2 and 3 to ensure good growth during the rainy period (mid July – September).

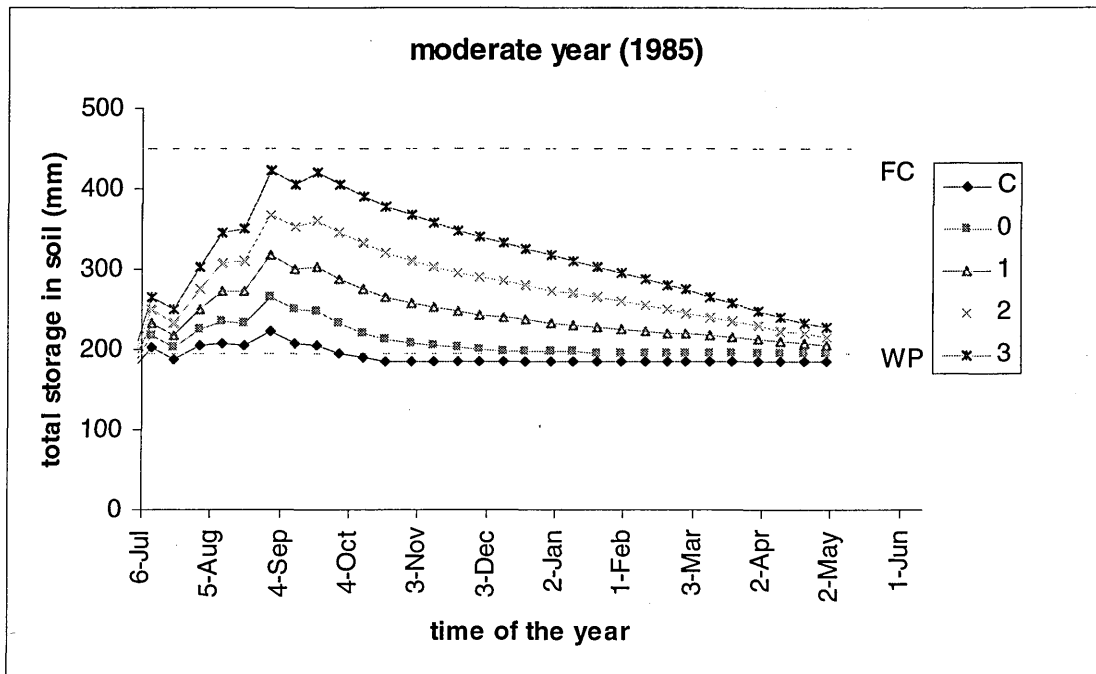


Figure 7.4: Temporal variation of soil water storage for the 5 treatments (C, 0, 1, 2 & 3) in a 1985 moderate year. Where FC and WP are as defined.

Treatments 2 and 3 were accompanied with some drainage out of the root zone (not shown) in some of the moderate years (e.g. 1964, 1967 and 1970). This may be due to high rainfall and reduced dry spells in these years. The total rainfall for these years were 536.1mm, 517.5mm and 536.1mm respectively, and the average dry spell between August and mid September was 2.3 days. Because of the reduced dry spell, the soil water during the August-mid September period was raised beyond the field capacity and consequently drained out of the root zone.

The scenarios were different in wet years as can be seen in figure 7.5. Here, although the model predicted insufficient soil water for the plant to go through to the next rainy season with treatment C, controlling runoff in the basin area alone (treatment 0) can provide enough water to sustain the plant in the dry season.

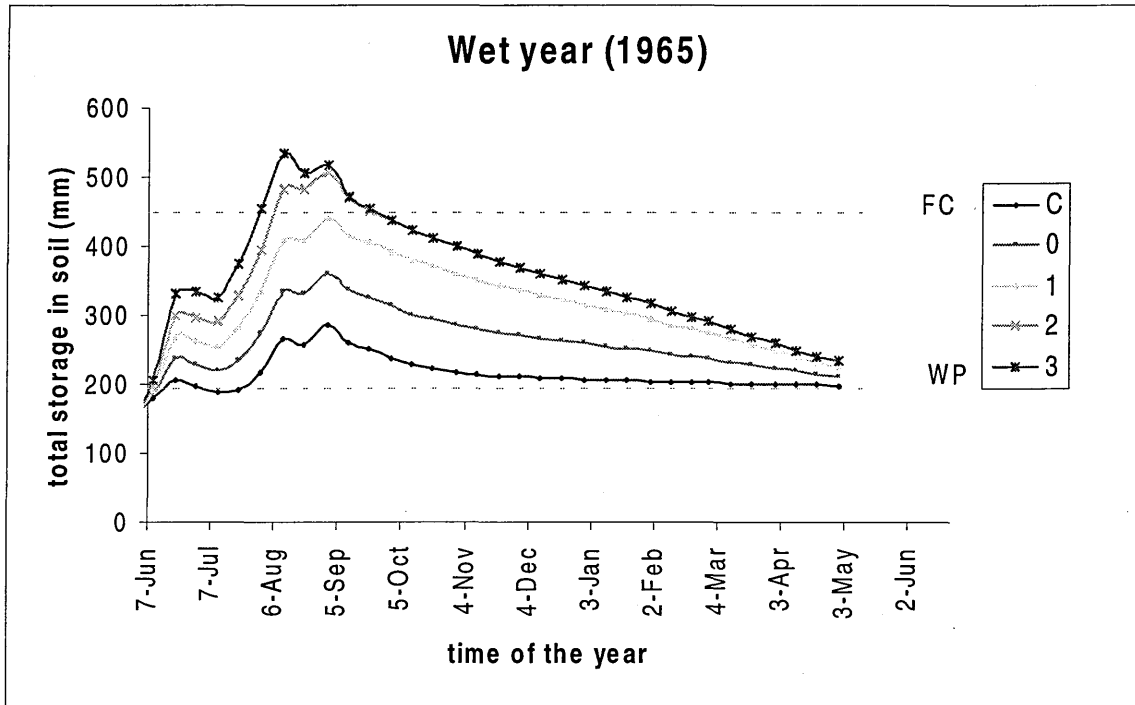


Figure 7.5: Temporal variation of soil water storage for the 5 treatments (C, 0, 1, 2 & 3) in a typical wet year (1965). Where FC and WP are as defined earlier.

The model predicted some drainage out of the root zone in 50% of the wet years with treatment 1 and in all the years with treatments 2 and 3. As in the moderate years, the drainage was in the August – mid September period. The period recorded 45.76% of the total rain in the seasons with an average rain per rainday of 15.3mm. The average rain per rainday in the wet years is significantly different from those in the dry and moderate years. Average dry spell in the period was 2.7 days (table 7.2) and this is not significantly different from the moderate years.

For the wet years, the variation of soil water storage with treatments 2 and 3 were the same from October to the end of the hydrological year (figure 7.6). This implies that any increase in the runoff area beyond 8m^2 ($r = 2$) does not have impact on the soil available water, as the excess water only results to drainage and will be of no benefit to the seedlings. However, bigger trees with deep rooting system can utilise this

water or the drainage water may even end up recharging the ground water. Therefore, in a wet year, a design that only controls runoff can provide enough water to sustain growth of the plant as predicted by the model.

b) Effect of soil cover

The predicted effect of covering the soil with perforated and solid polythelene on the seedling was analysed also in terms of the available water in the soil and actual transpiration. Water harvesting with a microcatchment design ratio of 2 was used for all treatments in the analysis.

1) Soil water

The predicted effect of cover (both partial and solid) on the total soil water storage is shown in figure 7.6. The difference between treatments was more in dry and moderate years than in wet years. Maximum difference of decadal total storage in the soil between bare soil and partially covered soil was 29.6mm and 30.8mm for dry and moderate years respectively. In the case of wet years the maximum difference was 22.8mm. For the difference between bare soil and solid cover treatments, the maximum difference were 45.3mm, 51.8mm and 40.4mm for the dry, moderate and wet years respectively.

In the dry and moderate years, the difference as predicted by the model was higher at the end of the rainy season. Soon after the rains, the soil is saturated in all treatments and the model predicted that the rate of evaporation (defined by U and α) was initially high in the bare treatment and that gave rise to the wide difference. As depletion of the soil water by processes of soil evaporation and transpiration by the plant continued into the dry season, the difference in soil water between the treatments also reduced. Most of the moisture conserved as a result of the cover was predicted to have been utilised in transpiration by the plant. By the first week of May (beginning of the next rainy season), the available water in all treatments was reduced to virtually the same value of around 200mm. The model predicted no drainage throughout the period simulated.

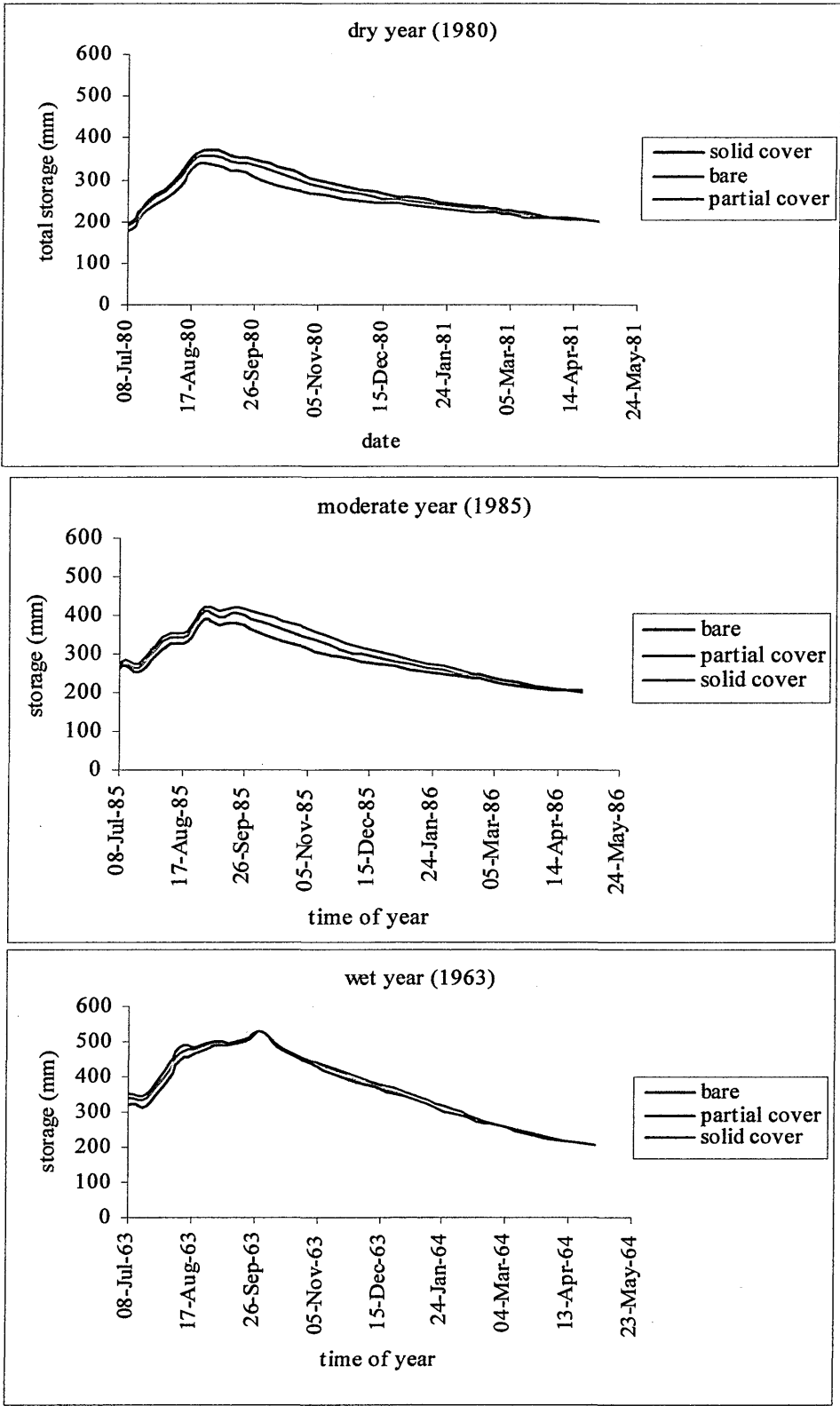


Figure 7.6: Effect of soil cover on soil water for dry, normal and wet years.

In the wet year, the model predicted that there was enough water in the soil to result into drainage with all treatments. Any measure designed to conserve water in the wet years would only increase the drainage, and the storage in the root zone as a result, will remain almost unaffected (see figure 7.6).

2) Transpiration

The model predicted similar trend with transpiration as with the soil available water. Figure 7.7 shows the temporal variation of actual transpiration in typical dry, moderate and wet years as predicted by the model. In all types of years, there was no obvious difference in the amount of water used in transpiration between treatments during the rainy season. The only difference between the treatments can be seen to start from October to the end of dry season for dry and moderate years as can be seen in figure 7.7. The difference between treatments was at maximum during the beginning of the dry season and then reduced gradually to less than 2mm towards the end of the dry season. There was no significant difference in the temporal variation of actual transpiration between treatments in the wet year, except for a slight improvement with the solid cover treatment between January and April. Maximum decadal transpiration reached about 17mm with the solid cover treatment and 15mm with the bare and partial cover treatments, and by the end of the dry season, the transpiration reduced to about 4mm with all treatments in the wet year.

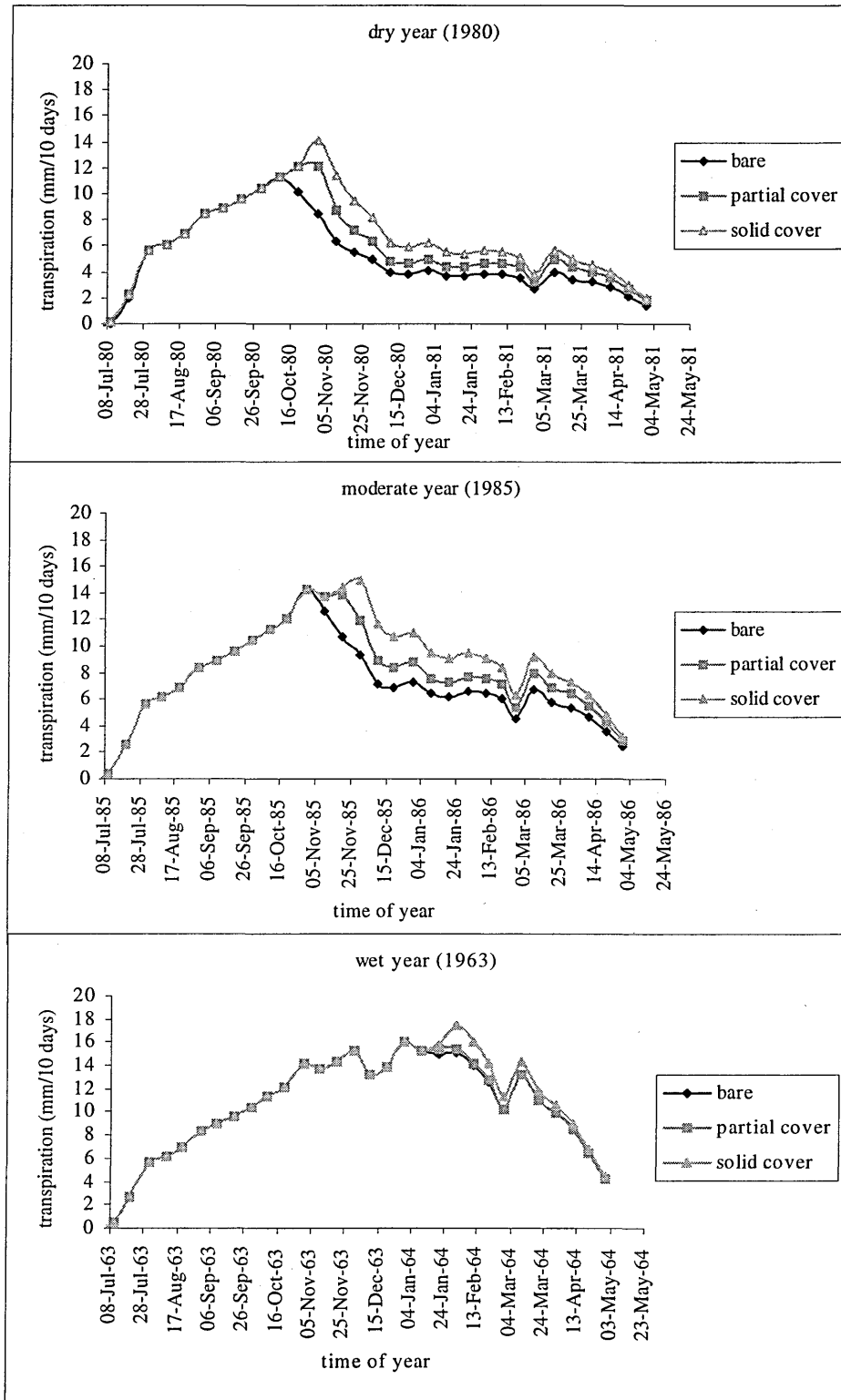


Figure 7.7: Effect of soil cover on actual transpiration of the plant in dry, moderate and wet years

This result indicates that the benefits to the plant of conserving moisture by covering the soil in this region are mostly in the dry and wet years. There was little or no benefit for conservation in wet years as far as the model shows.

3) Conclusion on the effect of soil cover

In terms of conserving enough soil moisture for the plant to utilise and extend its period of survival, it was predicted that covering the soil surface does not guarantee extension of the length of growing season for the plant. This was seen in the figure where the soil moisture status were almost the same towards the end of the periods simulated. It implies that provision of soil cover does not mean that catchment size can be reduced. However, the extra moisture conserved in the soil as a result of the cover can be used by the plant to enhance transpiration. This means rapid establishment of deep rooting system that can take up more water from deeper down in the soil profile and good growth of the seedlings.

7.3.3 Ponding

Result indicates that the time taken for the maximum depth of storage of 200mm to dry out was 32.8 hours on the Zurkaya site (which has the least infiltration capacity). During this period direct evaporation loss was around 5.5mm or 3% of the maximum storage. The loss was less on the more permeable sites (0.3% on the Dumburi site). It was seen that the basin area could be waterlogged for about one and a half days on some of the sites. If tillage can be applied, better infiltration can be achieved (Toutain, 1977) and the waterlogging period can be reduced.

It can be said that the loss of water due to direct evaporation from ponded water is small during its resident period. However, from the viewpoint of plant aeration and maximisation of storage, it is important to reduce the period of ponding. This can be achieved through improvement of infiltration. A doubling of the final infiltration rate at Zurkaya site, for instance, reduced the period of ponding from 32.8 hours to 15.4 hours. The loss due to direct evaporation as a result of the increase in infiltration was reduced from 3% to 1%.

7.4 CHAPTER SUMMARY

Results of preliminary field trial (see annex to this chapter) indicated that improvement in yield of cowpea and biomass and tree growth can be achieved when water harvesting technique is applied. Much of the improvement was observed at the lower part of the plots where the water concentrates. However, growths were stunted at the upper and middle portions of the plots and most of the trees have died three months after the end of the rainy season.

From the modelling results of all the years, it can be seen that augmenting rainfall with runoff water harvesting technique can provide enough water to sustain growth and ensure rapid establishment of the neem tree seedlings. The runoff water harvested is stored in the soil profile which, then can be used by the plant during the long dry season. However, due to reduced dry spell some deep percolation may result during the peak of the rainy season (August – mid September) especially in wet years.

This type of water harvesting is also most effective in sustaining crop growth when rain events are widely spread, i.e. at the start and end of the rains. It can be said that when rain events are frequent, there is probably sufficient infiltration to sustain growth without the benefit of water harvesting.

With a neem tree seedling planted in a 4m² basin area, an 8m² runoff area is likely to supplement the quantity of water required to sustain growth of the seedlings in all the three categories of years except for extreme dry years such as 1983. The risk in such extreme dry condition is slim and can be accepted in the design. Boers (1994) obtained a runoff area of 20m² for neem tree for Sokoto in Nigeria. This was higher than obtained in this study probably due to sandy nature of his runoff area and the difference in evapotranspiration demands. Therefore, the predictions by the BALANCE model indicate that a microcatchment size of 12m² ($r = 2$) can provide enough water to sustain growth in all types of years but with some deep drainage out of the root zone in wet years.

ANNEX**Field trial of runoff control**

A preliminary experiment was set up at Zurkaya site (12° 49.15'N, 11° 05.52'E) to test the effect of runoff harvesting on some selected plants by controlling runoff. Replicated bunded plots were laid out on the *fako* land situated between *tudu* and *tapki*. The long axis of the experiment lied across the slope, at a position on the *fako* where the slope is around 0.3 per cent.

The experimental design included three crop treatments (applied to plot pairs) and two water harvesting treatments (applied to individual plots) with replications (figure 7.1).

The experimental plots were laid out in pairs after careful topographic survey of the site. The size of each plot was 10 m × 10 m. One of the two (pair) plots was bordered on all four sides by a hand - made ridge about 20 cm high, with 1 m openings at the top on both sides along the slope line to allow for overflow. The control plots, although confined between bunded plots, were open at top and bottom to allow unrestricted runoff (figure A7.1). The site was fenced to deter animals from intrusion.

The crops were fodder species (mixture of stylo and gamba grass seeds), tree seedlings (*Acacia nilotica*) and conventional cowpea. The tree seedlings and the fodder species were obtained from the nursery and rangeland units at NEAZDP headquarters. Tree seedlings were planted in standard planting holes of 30 cm diameter and 30 cm depth and at spacings of 3 m × 3 m. This implies that each plot had 16 tree seedlings and the microcatchment size for each tree was about 6 m². Transplanting of the seedlings was carried out soon after enough moisture in the ground was observed. Cowpea was planted parallel to the bunds manually at a density of 2 seeds per hole and at distances of 30 cm between holes. The grass seeds were broadcast and lightly buried with soil using hand-hoe.

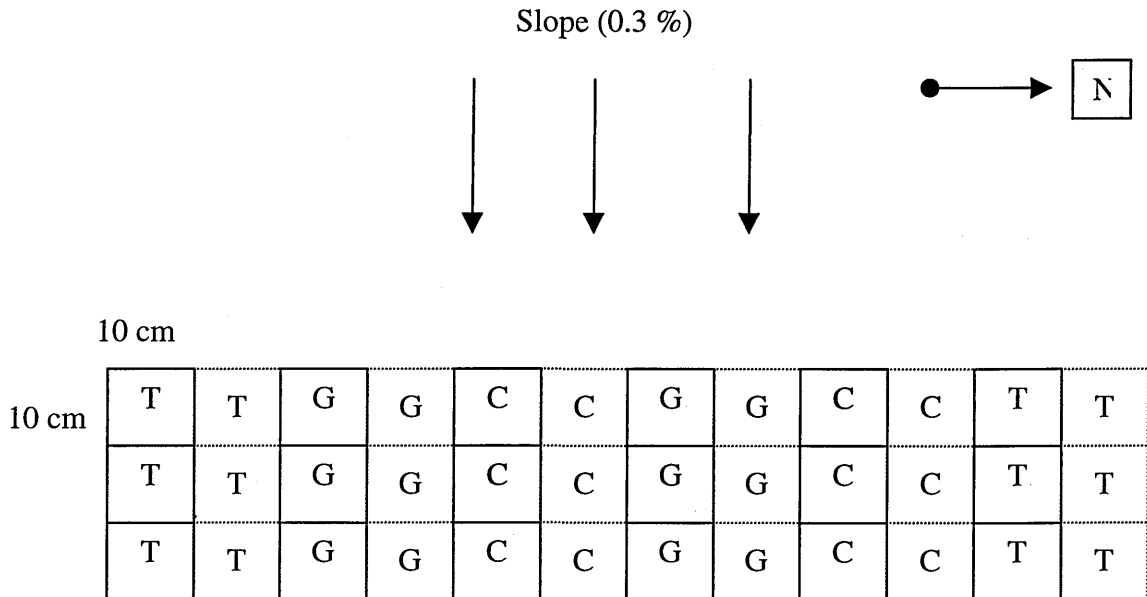


Figure A7.1: Experimental layout of water harvesting at the Zurkaya site.

(Where: — = banded plots, — = unbanded plots, C = cowpea,

G = mixture of stylo and grass, T = tree seedlings)

Measurements taken in the experiment included counts of established trees and cowpea plants; soil water contents measured gravimetrically at two weeks interval and yield of cowpea and above ground biomass for the grass.

Results and discussion

Results from the experiment showed that the advantages of capturing and retaining runoff to infiltrate were clearly demonstrated in the findings in terms of natural re-vegetation in the water zones created by bunds. Benefits were shown by the planted cowpea and gamba/stylo grasses with average yield and biomass on banded plots of 172.01 and 135.70 kg/ha compared to that on the unbanded plots of 74.41 and 22.90 kg/ha respectively (table A7.1). About 90% survival of the acacia tree seedlings was recorded in December on the banded plots.

Table A7.1: Yield of cowpea and above ground biomass of grass from banded and unbanded plots in kg/ha

	Row >>	1	2	3	Mean
Cowpea	<i>Banded</i>	220.60	144.21	151.23	172.01
	<i>Unbanded</i>	17.90	114.62	90.72	74.41*
Grass	<i>Banded</i>	47.06	224.34		135.70
	<i>Unbanded</i>	19.84	25.96		22.90

* significantly different from that of the banded plot.

Growth of all the plants was better at the lower parts of the banded plots. The lower parts served as collection points of the runoffs from the upper parts. As a result more water infiltrates into the profile which the plants eventually utilise for transpiration. At the upper parts of the plots, growth of the plants were stunted and infact some trees have actually died by December presumably because of inadequate water as revealed in table 7.2. The moisture contents of the soil at the upper parts of the banded plots were not much different from that of the unbanded plots.

Table A7.2: Moisture contents (in cm^3/cm^3) of the top 15 cm of the soil in mid September in banded (at lower and upper parts) and unbanded plots.

Banded		Unbanded
<i>lower</i>	<i>upper</i>	
0.10 (T)	0.07	0.09
0.20 (G)	0.08	0.06
0.14 (C)	0.08	0.08
0.17 (G)	0.14	0.08
0.19 (C)	0.13	0.10
0.16 (T)	0.12	

Where; T = tree, G = grass, C = cowpea.

About three months after the end of the rainy season (around December), all the tree seedlings on the control plots and most of those on the upper part of the banded plots had died.

Despite the provision of the overflow exits, there were occasional problems of overtopping and breaches. The breaches usually happened during very heavy raindays.

Conclusion from the experimental test

This initial research indicated that water harvesting structures (bunds) can stimulate the revival of natural vegetation and crop growth by retaining the runoff on gently sloping *fako* land which would otherwise be lost. Growth of the plants in the upper parts of the bunded plots was however, stunted due to the sloping nature of the field. Most of the water was observed to be concentrated at the lower third of the plots. This characteristic (where only one third of the plot is used for cropping) implies that only high value crops and trees may be suitable for the area.

CHAPTER EIGHT

GENERAL CONCLUSIONS AND RECOMMENDATIONS

8.1 CONCLUSION

8.1.1 General achievements

The followings are the contributions of this study to the advancement of scientific knowledge:

1. Identification and quantification of a unique land system (*fako*) suitable for water harvesting in the area using air-photo mosaics and field observations.
2. Providing new information regarding the area that had not been previously available, this includes rainfall intensity distribution, soil types & topography and runoff characteristics.
3. Development of a methodology for water harvesting that combines surface and subsurface distribution of water for the semi-arid north-east Nigeria.
4. Development of a rainfall-runoff model for microcatchment water harvesting on the *fako* lands of northeast Nigeria.
5. Suggestion of a suitable microcatchment size for the development and survival of neem (*Azadirachta indica*) tree seedlings in the area.
6. Showing the extent of the effect of soil cover with solid and perforated polyethelene on the length of survival of neem tree seedlings.
7. The research has also shown that the EUROSEM model (Morgan et. al, 1992) and BALANCE model (Hess, 1994) are applicable to the semi-arid northeast Nigerian conditions for runoff and water balance studies respectively.
8. A method for linking surface flow model (EUROSEM) with water balance model (BALANCE) was developed.

8.1.2 Specific conclusions

The land systems

In pursuance of the objectives of this research work (as stated in chapter I), the study area was first surveyed and evaluated as to its suitability for water harvesting. As a result, four distinct land systems were identified. The land systems were *tudu*, *fako*, *tapki* and *fadama*. *Tudu* being predominantly sandy in nature has low water holding capacity and therefore, may not be suitable for water harvesting. It covers the largest part of the study area. The local people cultivate this type of land for the production of seasonal crops such as sorghum, millet, groundnut and cowpea.

Fakos are degraded patches of lands with little or no vegetative growth. Scattered around the study area, they range in size from 1 to 10 hectares and cover about 3 % of the total area. Bulk density values of the *fako* soils range from 1.3 to 1.61 gcm⁻³. Mechanical analysis of the soils revealed that the texture of the soil is predominantly clay loam. The hydraulic characteristics of the soil are such that the infiltration rate is low (values as low as 2 mm/h were recorded) and the water retention characteristics indicated high water holding capacity. Volumetric soil moisture content at saturation (0 kPa) for the *fako* ranged from 38 % to 55 %, At field capacity (at 10 kPa) the volume water fraction was between 17 % and 32 % and at permanent wilting point (at 1500 kPa) the range was from 11 % to 24 %. The high bulk density restricts water infiltration and root development thereby rendering these lands bare. Values of slope measurements varied from 0.3 % to 0.5 %. The local people do not attempt to cultivate this type of land system.

The *tapkis* are inter-dunal depressions that hold large bodies of water during and after the rainy season. They can remain ponded for up to 3 or 4 months after the end of the rains. The soils are usually deep and may crack when dry. Some species of trees and grasses can be seen growing in them.

The *fako* lands have characteristics suitable for water harvesting systems. The high water holding capacity means that runoff can be harvested and stored in the profile to be used by plants during dry periods thereby requiring no expensive construction work for storage. However, for the water to be stored in the soil profile of *fako* lands, the infiltration characteristic has to be improved. The surface of the soil where the water is to be stored should be improved to encourage infiltration and reduce the risk of waterlogging and excessive evaporation.

The climate

Climatic data for the area were gathered. High-resolution rainfall data from seven stations were collected between 1992 and 1994 to obtain data for 13 site-years. In addition, daily rainfall data for three decades (1961-1990) were also obtained. Other climate data such as temperature, relative humidity, sunshine and evaporation were also collected from Nguru meteorological station and NEAZDP headquarters at Garin Alkali.

Climatic characteristics of the study area are such that plants, both seasonal and perennial, find it difficult to survive. The rainfall is marginal and is compounded by high evaporation demand and runoff losses on some land systems (e.g. *fako*). The annual average of the rainfall for the 13 site-years is 408.8 mm with a standard deviation of 108.8 mm. This is slightly less than the 30-year average probably as a result of the downward trend of rainfall in the area (Hess et al., 1995). Intensity analysis of the storms for the 13 site-years revealed that the rains are slightly higher in intensity at the beginning of the season than towards the end of the rainy season. Average storm intensity over the entire rainy season was found to be 22.47 mm/h with a coefficient of variation of about 54 %.

Field Trials

Preliminary investigations of runoff control and soil evaporation control on the *fako* lands were conducted at Zurkaya and Jawa sites in 1994 and 1995.

1. *Runoff water harvesting*

Initial field trial of runoff control indicated that water harvesting on the *fako* lands is feasible and has good prospects. The trial did not involve costly structures and can easily be adopted by the local people. In the experiment, potential benefits of harvested runoff were demonstrated in terms of establishment of tree seedlings (*Acacia nilotica*), yield of cowpea and spontaneous revegetation of land with grass seedlings (*Gamba/Stylo*). The tree seedlings in the bunded plots (especially those near the bunds at the lower ends) survived for up to 3 months after the end of the rainy season. However, growths were stunted at the upper and middle portions of the bunded plots. Trees in the control plots died soon after the rains stopped.

The main design criterion of a rainwater harvesting system is its runoff-basin area ratio - the ratio of the area of runoff to the area of the basin (or run-on area). The tree experimental trial represented a microcatchment with an approximate runoff area to basin area ratio of 2:1.

Above ground biomass of grass and cowpea yield were about 4 times in the bunded plots compared to those in the control plots.

2. *Soil evaporation*

An experiment to determine the effect of cover on soil evaporation and temporal variation of soil moisture content on the *fako* areas was conducted. The experiment showed that soil cover can increase the available soil moisture by suppressing direct evaporation. Though solid cover treatment provides the maximum suppression of evaporation, the partial cover treatment is recommended as, in addition to reducing evaporation, it can at the same time allow rainwater infiltration into the soil.

Modelling

Models were applied for the water harvesting research on the *fako* lands. Models for the collection of runoff from the *fako* lands and for water balance have been discussed. Two models for surface runoff (KINEROS by Woolhiser et. al, (1990)

and EUROSEM by Morgan et. al, (1992)), and three for water balance (SHE by Abbott et. al, (1986), SWATRE by Belmans et.al (1983) and BALANCE by Hess, (1994)) were reviewed based on their concepts and structures out of which two were selected. The EUROSEM was used to simulate runoff on the surface of the *fako* lands from which a simplified runoff model suitable for use in water harvesting studies was ultimately developed. The BALANCE model was used to simulate water balance of cropped *fako* land. To apply the models in the semi-arid zone of Nigeria, the models (only evaporation process in the case of BALANCE) were calibrated and validated with data from experiments conducted on the field. To effectively model the soil-water-atmosphere of the area, data on soil and climate for the area were gathered.

The EUROSEM model

The EUROSEM deterministic model was used to simulate runoff on the *fako* lands. The model was first calibrated and validated using field data (Klemes, 1986). Runoff was generated on the field from various intensities (ranged from 25 to 169 mmh⁻¹) produced by a rainfall simulator (USDA, 1972). The range of intensity reflects the values for northern Nigeria as reported in the literature (Kowal and Kassam, 1976).

Sensitivity analysis of the EUROSEM model revealed that the maximum relative saturation of the soil, effective net capillary drive, saturated hydraulic conductivity and the initial relative saturation of the soil are the most sensitive parameters in the model as far as runoff volume is concerned. The runoff data was divided into two with one part used for calibration and the other used for validation (Klemes, 1986). Calibration of the model was achieved by varying three parameters (maximum relative saturation, porosity and effective net capillary drive) within their range values until best fit between observed and simulated was achieved. Validation was achieved by comparing predicted runoff volumes with observed data not used in calibration. After validation, the model was evaluated and the summary statistics confirmed that it could simulate surface runoff with an r^2 value of 0.83 and coefficient of efficiency of 0.74 on the *fake* lands of northeast Nigeria. Quinton (1994) reported result of his validation of the EUROSEM model on Woburn site in

the UK that also showed good agreement between measured and simulated runoffs. Simulation results of this study showed better agreements between field and model values. While Quinton (1994) used natural rainfall and assumed initial moisture content, in this study, rainfall was simulated and initial conditions were measured. Natural rain fluctuates continuously and is difficult to control.

The linear runoff model

A linear regression model for predicting runoff from daily rainfall was developed for the *fako* lands of northeast arid region of Nigeria. The linear model can be regarded as an integral expression of the physiographic and climatic characteristics that govern the relations between daily rainfall and runoff on the *fako* areas. The runoff coefficient and the threshold value were 0.44 mm/mm and 16 mm respectively. The threshold value obtained was lower than that predicted by the HEC model (Hydrologic Engineering Center, 1990) under dry conditions on silt loam soils (Duru and Hjelmfelt, 1994). Correlation coefficient of 0.79 was obtained for the rainfall-runoff relationship, which means that the model can be used for prediction of runoff from rainfall.

Due to the variation of intensity in the rainy season, the linear model under-estimated runoff (and hence runoff efficiency) at the beginning of the rains and over-estimated towards the end of the rains. The average runoff efficiency obtained on a typical *fako* land was about 0.16.

Compared to the curve number model for predicting runoff from daily storms, the linear model is as good. The simplicity and ease with which the linear model can be used places it at an advantage over the curve number model. However, the linear model can be used only for the *fako* lands of northeast Nigeria from which soil and rainfall data were gathered and used in the development of the model.

The BALANCE model

The Ritchie equation for evaporation in BALANCE model was calibrated and validated using soil moisture content of the *fako* areas of northeast arid zone of

Nigeria. Calibration was achieved by using the parameters that define the soil evaporation (U and α) in the model. The values of these parameters obtained after calibration were 19 mm and $4.5 \text{ mmday}^{-0.5}$ for the bare treatment, 20 mm and $2.2 \text{ mmday}^{-0.5}$ for the perforated cover treatment and 20 mm and $0.5 \text{ mmday}^{-0.5}$ for the solid cover treatment. A plot of measured versus simulated moisture content gave coefficient of determination and coefficient of efficiency of 0.9 & 0.86 and 0.89 & 0.89 in calibration and validation respectively. It was also observed that the BALANCE model predicted shorter drying cycle for the *fako* areas of the northeast arid zone of Nigeria.

With accurate estimates of the soil hydraulic parameters and good calibration, the BALANCE model can be used to simulate water balance components on the *fako* areas of the northeast arid region of Nigeria.

Model application to water harvesting

For tree growth, a microcatchment water harvesting technique is recommended (Critchley, 1991; Boers, 1994; AGROMISA, 1997). Modelling technique was applied to evaluate proper microcatchment size for the survival of neem tree seedlings on *fako* lands. Model simulation results for 30 years (1961-1990) showed that augmenting rainfall with runoff water harvesting technique could provide enough water to sustain growth and ensure rapid establishment of the neem tree seedlings. The runoff water harvested is stored in the soil profile, which is used by the plant during the long dry season.

With a neem tree seedling planted in a 4m^2 -basin area, a microcatchment with a design that only stops runoff (ratio of zero) cannot ensure survival of the seedlings in all types of years. A design with a ratio greater than two on the other hand will result to deep percolation in some normal and in most of the wet years. A design with a 12m^2 microcatchment size (i.e. 8m^2 runoff area) is likely to provide enough water that can sustain growth of the neem tree in all categories of years (dry, normal and wet) but with some drainage out of the root zone in some wet years.

For a tree seedling in the *fako* area, losses vary mainly because of evaporation. Boers (1994) reported that variation in losses at Sadore (Niger) and Katsina (Nigeria) were mainly due to deep percolation. The difference in the loss mechanism may be due to the type and depth of soil. The *fako* soil used in this study was heavier. Deep percolation losses were predicted only in wet years and some moderate years. The losses were all during the peak periods (August and September) of the rainy season when rain days are closely spaced.

8.1.3 Limitations

As is the case with many studies, the work carried out in this study was not without limitations. Due to time constraints and some logistical problems, there were some limitations in the data collected in the field. For the rainfall simulation experiment, water was difficult to get during the experiments as the *tapkis* have dried up at that time. Long distances had to be covered to collect water for simulations. More replications of rainfall-runoff simulations and on different other sites would have provided better representation for the area. Also, the soil evaporation trial needed more frequent monitoring which would have shed more light on the drying process for the area. Frequent monitoring was difficult to conduct due to transportation, incidences of equipment failure (e.g. the weighing machine) and other related problems.

The hard nature of the *fako* lands and the lack of better augering tools (e.g. power auger) placed some constraints on the number of holes made and samples collected for the inverse auger-hole and permeameter methods of hydraulic conductivity determination and soil moisture monitoring.

The different microcatchment sizes evaluated using models could not be tested on the field due to time constraints.

8.2 RECOMMENDATIONS

The following are some recommendations related to the present study that require further research.

1. Due to reduced rainfall over the years (Hess et al., 1995) compounded by land degradation (Abdalla, 1994) there are serious practical problems of water that need prompt actions such as water harvesting. As the study is largely model-based, there is the need to test the planting of neem trees in the microcatchments on the *fakos* and to evaluate the effect on the environment before promoting it.
2. The occasional breaching and overtopping of the bunds experienced during the field trial need investigations to find ways of stabilizing the bunds.
3. Different types of mulching materials should be investigated and evaluated with a view to recommending one that can significantly reduce evaporation in the basin area without hindering water infiltration.
4. Measures to improve infiltration and water storage in the basin area need further investigations. Tillage for example, is required on badly degraded soils or for those that undergo severe hardening during the dry season.
5. As the water in the *tapkis* is essential for survival of livestock during the dry season, the impact of water harvesting on the water balance of the *tapkis* needs assessment.

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APPENDICES

APPENDIX A

**RAINFALL-RUNOFF SIMULATION DATA FOR ZURKAYA, JAWA AND
DUMBURI SITES**

(a) *Zurkaya site.*

Rain characteristics and soil initial moisture content	TIME(h:min:s)		volume of runoff collected (litres)	Duration (min)	Runoff rate (lit/min)
	(h:min:s)				
Average Intensity = 127 mm/h Initial moisture = 0.024 Rain started at 9.37 am am.	TIME (h:min:s)				
	from	to			
	9:41:15	9:41:30	0.96	0.25	3.84
	9:42:45	9:43:00	1.07	0.25	4.28
	9:45:15	9:45:30	1.06	0.25	4.24
	9:48:15	9:48:30	1.13	0.25	4.52
	9:51:00	9:51:15	1.2	0.25	4.80
	9:53:30	9:53:45	1.12	0.25	4.48
Average Intensity = 38 mm/h Initial moisture = 0.084 Rain started at 9.45 am	9:57:00	9:58:00	0.35	1.00	0.35
	9:59:30	10:00:30	0.55	1.00	0.55
	10:01:45	10:02:30	0.72	0.75	0.96
	10:03:10	10:04:10	0.95	1.00	0.95
	10:05:10	10:06:00	0.95	0.83	1.14
	10:07:30	10:08:30	1.05	1.00	1.05
	10:09:30	10:10:30	1.05	1.00	1.05
	10:12:35	10:13:35	0.92	1.00	0.92

Appendices

Average Intensity = 156 mm/h Initial moisture = 0.122 Rain started at 4.10 pm	4:13:20	4:13:35	0.97	0.25	3.88
	4:16:20	4:16:35	1.09	0.25	4.36
	4:17:30	4:17:35	1.10	0.167	6.59
	4:18:30	4:18:45	1.20	0.25	4.80
Average Intensity = 50 mm/h Initial moisture = sat. Rain started at 4.30 pm	4:31:50	4:32:50	0.80	1.00	0.80
	4:33:30	4:34:30	0.90	1.00	0.90
	4:35:00	4:36:00	1.03	1.00	1.03
Average Intensity = 50 mm/h Initial moisture = 0.07 Rain started at 4.13 pm	4:18:00	4:19:15	0.51	1.25	0.41
	4:22:00	4: 22:30	0.48	0.50	0.96
	4:25:30	4: 26:00	0.57	0.50	1.14
	4:29:00	4: 29:30	0.67	0.50	1.34
Average Intensity = 41 mm/h Initial moisture = 0.08 Rain started at 4.09 pm	4:19: 00	4.2	0.26	1.00	0.26
	4:22:30	4.23.30	0.46	1.00	0.46
	4:26:00	4.26.40	0.63	0.67	0.94
	4:28:00	4.28.45	0.71	0.75	0.95
	4:03:00	4.30.45	0.72	0.75	0.96
Average Intensity = 162 mm/h Initial moisture = 0.107 Rain started at 9.07 am	9:08:05	9.08.50	0.61	0.75	0.81
	9:10:15	9.10.30	1.21	0.25	4.84
	9:14:30	9.14.45	1.23	0.25	4.92
	9:15:20	9.15.45	1.25	0.25	5.00
	09:17:00	9.17.15	1.26	0.25	5.04

Appendices

Average Intensity = 135 mm/h Initial moisture = 0.107 Rain started at 10.07 am	10:08:05	10.08.20	0.61	0.25	2.44
	10:10:15	10.10.30	1.12	0.25	4.48
	10:14:30	10.14.45	1.23	0.25	4.92
	10:15:20	10.15.35	1.25	0.25	5.00
	10:17:00	10.17.15	1.26	0.25	5.04
Average Intensity = 32 mm/h Initial moisture = 0.119 Rain started at 9.14 am	9:19:00	9.19.50	0.5	0.83	0.60
	9:21:10	9.21.40	0.5	0.5	1.00
	9:23:00	9.23.30	0.54	0.5	1.08
	9:25:15	9.25.40	0.55	0.5	1.10
	9:28:00	9.28.30	0.53	0.5	1.06
	9:30:15	9.30.45	0.54	0.5	1.08
Average Intensity = 50 mm/h Initial moisture = 0.12 Rain started at 4.14 pm	4:15:00	4:15:40	0.15	0.6667	0.22
	4:17:00	4:17:30	0.36	0.5	0.72
	4:18:30	4:18:45	0.23	0.25	0.92
	4:20:15	4:20:30	0.25	0.25	1.00
	4:22:00	4:22:15	0.3	0.25	1.20
	4:25:10	4:25:25	0.32	0.25	1.28
	4:27:15	4:27:30	0.35	0.25	1.40
Average Intensity = 58 mm/h Initial moisture = 0.106 Rain started at 4.11 pm	4.13.10	4.13.50	0.210	0.6667	0.31
	4.15.00	4.15.30	0.300	0.5	0.60
	4.16.45	4.17:00	0.300	0.25	1.20
	4.18.15	4.18.30	0.340	0.25	1.36
	4.19.15	4.19.30	0.360	0.25	1.44
	4.20.45	4:21:00	0.380	0.25	1.52

Appendices

(b) Jawa site

Average Intensity = 145 mm/h Initial moisture = 0.0221 Rain started at 5.00 pm	5.00:00	5.02.00	0.78	2.00	0.39
	5.04:00	5.04.30	0.66	0.50	1.32
	5.05:00	5.05.15	0.86	0.25	3.44
	5.06:00	5.06.10	0.90	0.17	5.40
	5.07:00	5.07.12	0.92	0.20	4.60
	5.08:00	5.08.15	0.93	0.25	3.72
	5.09:00	5.09.15	0.95	0.25	3.80
	5.10:00	5.10.15	1.00	0.25	4.00
	5.12:00	5.12.10	0.86	0.17	5.16
Average Intensity = 30 mm/h Initial moisture = fc Rain started at 8.42.30 am	9:03:00	9:03.00	0.25	3.00	0.08
	9:06:00	9:08.00	0.57	2.00	0.29
	9:09:00	9.11.30	0.63	2.50	0.25
	9:12:00	9.13.40	0.64	1.67	0.38
	9:16:15	9.17.45	0.68	1.50	0.45
Average Intensity = 75 mm/h Initial moisture = fc Rain started at 3.33.30 pm	3:37:30	3:39:30	0.17	2.00	0.09
	3:40:30	3:41:30	1.00	1.00	1.00
	3:42:30	3:43:30	0.73	1.00	0.73
	3:44:30	3:45:30	0.93	1.00	0.93
	3:46:30	3:47:15	1.06	0.75	1.41
	3:48:30	3:49:00	1.03	0.50	2.06
	3:50:00	3.50.20	0.99	0.67	1.48
	3.53:00	3.53.20	0.84	0.67	1.26

Appendices

Average Intensity = 156 mm/h Initial moisture =0.1532 Rain started at 4.26 pm	4:27:30	4:28:00	0.83	0.50	1.66
	4:29:00	4:29:15	0.95	0.25	3.80
	4:30:30	4.30.40	1.00	0.17	6.00
	4:32:00	4.32.10	1.00	0.17	6.00
Average Intensity = 169 mm/h Initial moisture =0.1404 Rain started at 9.23 am	9:24:40	9:25:40	0.90	1.00	0.90
	9:27:00	9:27:15	0.95	0.25	3.80
	9:28:30	9:28:45	0.85	0.25	3.40
	9:30:00	9:30:15	0.96	0.25	3.84
	9:31:30	9:31:45	1.23	0.25	4.92
	9:32:15	9:32:25	1.26	0.17	7.56
	9:35:00	9:35:10	1.30	0.17	7.80
	9:37:00	9:37:10	1.25	0.17	7.50
	9:38:30	9:38:40	1.06	0.17	6.36
	9:40:00	9:40:10	1.06	0.17	6.36
Average Intensity = 60 mm/h Initial moisture =0.321 Rain started at 9.55 am	9:57:15	9.58.00	1.16	0.75	1.55
	9:59:15	10:00:00	1.17	0.75	1.56
	10:01:30	10:02:15	1.19	0.75	1.59
	10:03:15	10:04:00	1.29	0.75	1.72
Average Intensity = 65 mm/h Initial moisture =0.079 Rain started at 5.33 pm	5:35:30	5.36.30	0.80	1.00	0.80
	5:37:15	5.37.30	0.22	0.25	0.88
	5:38:30	5.38.45	0.36	0.25	1.44

Appendices

Average Intensity = 93 mm/h Initial moisture = Rain started at 4.18 pm	4:21:35	4.21.45	1.08	0.17	6.48
	4.:23:00	4.23.10	0.94	0.17	5.64
	4:24:10	4.24.20	0.98	0.17	5.88
	4:26:20	4.26.30	1.04	0.17	6.24
	4:28:00	4.28.10	1.04	0.17	6.24
	4:29:30	4.29.40	1.04	0.17	6.24
	4:31:00	4.31.10	0.93	0.17	5.58
	4:32:00	4.32.10	0.93	0.17	5.58
	4:33:15	4.33.25	0.99	0.17	5.94
	4:35:45	4.35.55	0.94	0.17	5.64
Average Intensity = 25 mm/h Initial moisture = 0.32 Rain started at 3.40 pm	3:43:35	3:44:35	0.74	1.00	0.74
	3:47:15	3:48:15	0.59	1.00	0.59
	3:49:15	3:50:15	0.50	1.00	0.5
	3:51:20	3:52:20	0.62	1.00	0.62
	3:56:30	3:57:30	0.65	1.00	0.65
	3:58:45	3:59:45	0.73	1.00	0.73
	4:00:45	4:01:65	0.51	1.00	0.51
	4:08:00	4:09:00	0.63	1.00	0.63
	4:10:00	4:11:00	0.57	1.00	0.57

(c) Dumburi Site

A ve ra ge Int en sit y =	4:57:00	4:57:30	0.45	0.50	0.90
	4:58:20	4:58:30	0.52	0.17	3.12
	4:59:30	4:59:40	0.56	0.17	3.36
	5:00:40	5:00:50	0.65	0.17	3.90

	5:01:30	5:01:40	0.73	0.17	4.38
	5:02:25	5:02:35	0.77	0.17	4.62
	5:04:25	5:04:35	0.83	0.17	4.98
Average Intensity = 52.5 mm/h Initial moisture 0.323 Rain started at 5.26 pm	5:28:15	5:30:15	0.20	2.00	0.10
	5:31:20	5:32:05	0.30	0.75	0.40
	5:34:30	5:35:00	0.43	0.50	0.86
	5:36:30	5:37:00	0.60	0.50	1.20
	5:37:30	5:38:00	0.48	0.50	0.96
	5:39:00	5:40:00	0.50	1.00	0.50
	5:41:00	5:42:00	0.50	1.00	0.50
	5:42:45	5:43:15	0.50	0.50	1.00
Average Intensity = 120 mm/h Initial moisture =sat Rain started at 5.33 pm	5:37:30	5:38:30	0.21	1.00	0.21
	5:39:35	5:39:55	0.71	0.33	2.13
	5:41:00	5:41:10	0.82	0.17	4.92
	5:42:00	5:42:10	0.83	0.17	4.98
	4:50:00	4:50:30	0.30	0.50	0.60
	4:53:00	4:53:15	0.30	0.25	1.20
	4:55:00	4:55:15	0.41	0.25	1.64
	4:56:10	4:56:25	0.40	0.25	1.60
Average Intensity = 72 mm/h Initial moisture =sat Rain started at 4.48 pm	4:57:30	4:57:45	0.41	0.25	1.64
	5:17:30	5:18:00	1.38	0.50	2.76
	5:18:30	5:19:00	1.92	0.50	3.84
	5:20:40	5:20:50	1.05	0.17	6.30
	5:21:50	5:22:00	1.05	0.17	6.30

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Average Intensity = 65 mm/h Initial moisture =sat Rain started at 4.43 pm	4:45:30	4:46:30	0.80	1.00	0.80
	4:47:15	4:47:30	0.22	0.25	0.88
	4:48:20	4:48:35	0.36	0.25	1.44
Average Intensity = 41 mm/h Initial moisture =sat Rain started at 5.32 pm	5:34:00	5:35:00	1.17	1.00	1.17
	5:35:30	5:37:00	1.84	1.50	1.23
	5:38:00	5:39:00	1.31	1.00	1.31
	5:40:00	5:41:00	1.38	1.00	1.38
Average Intensity = 48 mm/h Initial moisture =sat Rain started at 5.13 pm	5:26:00	5:27:00	0.10	0.50	0.20
	5:28:00	5:29:00	0.13	0.50	0.25
	5:32:00	5:33:00	0.19	0.50	0.38
	5:34:00	5:35:00	0.19	0.50	0.38

APPENDIX B

MOISTURE CONTENT DATA FOR ZURKAYA AND JAWA SITES

ZURKAYA						
Treatment	Replicate	Depth (cm)	Date			
			08/10/95	26/10/95	20/11/95	14/01/96
Bare soil	1	5	0.2520	0.0319	0.0306	0.0226
		10	0.2137	0.0924	0.0361	0.0384
		15	0.1894	0.1313	0.0634	0.0540
		20	0.1472	0.0914	0.0676	0.0546
		25	0.1489	0.0980	0.0784	0.0605
		30	0.1117	0.0972	0.0820	0.0814
	2	5	0.2509	0.0394	0.0319	0.0263
		10	0.2291	0.1248	0.0524	0.0312
		15	0.1861	0.1534	0.0674	0.0593
		20	0.1262	0.1199	0.0699	0.0585
		25	0.1241	0.1058	0.0759	0.0614
		30	0.1132	0.1045	0.0917	0.0804
	3	5	0.2506	0.0586	0.0335	0.0586
		10	0.2176	0.0596	0.0438	0.0596
		15	0.1687	0.1379	0.0652	0.1379
		20	0.1388	0.1065	0.0766	0.1065
		25	0.1244	0.1079	0.0782	0.1079
		30	0.1209	0.0936	0.0814	0.0936

Solid cover	1	5	0.2433	0.1895	0.1120	0.1078
		10	0.2105	0.1687	0.1589	0.1215
		15	0.1632	0.1670	0.1602	0.1393
		20	0.1354	0.1582	0.1443	0.1170
		25	0.1095	0.0940	0.1014	0.0854
		30	0.1198		0.1029	0.0669
	2	5	0.2393	0.2208	0.1170	0.1065
		10	0.2318	0.1865	0.1744	0.1200
		15	0.2040	0.1873	0.1763	0.1378
		20	0.1496	0.1773	0.1734	0.1129
		25	0.1486	0.1437	0.1445	0.0872
		30	0.1036	-	0.0735	0.0730
	3	5	0.2378	0.2068	0.1202	0.0989
		10	0.2207	0.1466	0.1472	0.1245
		15	0.2225	0.1214	0.1559	0.1191
		20	0.1291	0.1096	0.1219	0.1362
		25	0.1212	-	0.0972	0.0880
		30	0.1219	-	0.0972	0.0763
Perforated cover	1	5	0.2452	0.1424	0.0472	0.0482
		10	0.2460	0.1495	0.1145	0.0530
		15	0.1895	0.1672	0.1131	0.0874
		20	0.1168	0.1515	0.1251	0.0790
		25	0.1089	0.1399	0.1377	0.0544
		30	0.1148		0.0960	0.0604

Perforated cover continued	2	5	0.2767	0.1339	0.0644	0.0190
		10	0.2561	0.1694	0.1253	0.0414
		15	0.2387	0.1670	0.1134	0.0656
		20	0.1502	0.1399	0.1265	0.0786
		25	0.1116	0.1300	0.1290	0.0754
		30	0.1106			
	3	5	0.2218	0.1501	0.0515	0.0542
		10	0.2002	0.1715	0.1257	0.0680
		15	0.1846	0.1879	0.1127	0.0929
		20	0.1495	0.1901	0.1301	0.0916
		25	0.1355	0.1467	0.1273	0.0821
		30	0.1173			
JAWA						
Treatment	Replicate	Depth (cm)	Date			
			08/10/95	26/10/95	20/11/95	14/01/96
Bare soil	1	5	0.2435	0.0255	0.0310	0.0237
		10	0.2430	0.0742	0.0450	0.0476
		15	0.2437	0.1390	0.0868	0.0695
		20	0.1540	0.1206	0.1098	0.1012
		25	0.1322	0.1337	0.1079	0.1130
		30	0.1158	0.1174	0.0997	0.1063

Bare soil continued	2	5	0.2828	0.0215	0.0361	0.0370
		10	0.2971	0.1540	0.0606	0.0527
		15	0.2896	0.1957	0.0976	0.0831
		20	0.1782	0.1311	0.1329	0.0934
		25	0.1150	0.1041	0.1155	0.1036
		30	0.1149	0.1093	0.1072	0.1061
	3	5	0.2745	0.0223	0.0265	0.0273
		10	0.2405	0.0815	0.0517	0.0580
		15	0.2278	0.1085	0.0924	0.0616
		20	0.1696	0.1173	0.0995	0.0787
		25	0.1377	0.1095	0.1070	0.0955
		30	0.1183	0.1040	0.1063	0.1017
Solid cover	1	5	0.2236	0.1754	0.1195	0.0968
		10	0.2270	0.2193	0.1514	0.1397
		15	0.1585	0.1923	0.1511	0.1424
		20	0.1466	0.1603	0.1383	0.1359
		25	0.1325	0.1315	0.1453	0.1180
		30	0.1221	0.1171	0.1303	0.1099
	2	5	0.2273	0.2013	0.1185	0.1061
		10	0.2450	0.2235	0.1644	0.1440
		15	0.2487	0.2045	0.1903	0.1576
		20	0.1767	0.1778	0.1379	0.1460
		25	0.1242	0.1397	0.1138	0.1299
		30	0.1125	0.1302	0.1153	0.0930

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Solid cover continued	3	5	0.2353	0.1625	0.0991	0.0970
		10	0.2239	0.2134	0.1263	0.1567
		15	0.2256	0.1935	0.1886	0.1508
		20	0.1544	0.1557	0.1495	0.1471
		25	0.1312	0.1251	0.1366	0.1099
		30	0.1115	0.1203	0.1151	0.0856
Perforated cover	1	5	0.2193	0.1228	0.0566	0.0458
		10	0.2325	0.2003	0.1078	0.0898
		15	0.2462	0.1915	0.1142	0.0902
		20	0.1611	0.1685	0.1270	0.1215
		25	0.1261	0.1391	0.1378	0.1069
		30	0.1154	0.1123	0.1015	0.1054
	2	5	0.2336	0.1127	0.0938	0.0850
		10	0.2521	0.1828	0.1396	0.1093
		15	0.2591	0.2239	0.1527	0.1306
		20	0.1380	0.1558	0.1368	0.1066
		25	0.1261	0.1198	0.1214	0.0974
		30	0.1149	0.1250	0.1118	0.1002
	3	5	0.2539	0.1465	0.0797	0.0411
		10	0.2770	0.1909	0.1213	0.0580
		15	0.2648	0.1752	0.1279	0.0959
		20	0.1324	0.1460	0.1344	0.1262
		25	0.1114	0.1328	0.1183	0.0981
		30	0.1080	0.1278	0.1159	0.0918

APPENDIX C

EXAMPLE OF RAINFALL FILE FOR EUROSEM MODEL

EUROSEM Rainfall Input Data V3 11/93

#

Gage Network Data

#

NUM. OF RAINGAGES MAX. NUM. OF TIME-DEPTH DATA PAIRS FOR ALL
GAGES

(NGAGES)

(MAXND)

1

13

#

There must be NELE pairs of (GAGE WEIGHT) data

*

ELE. NUM. (J)	RAINGAGE	WEIGHT
-----	-----	-----
1	1	1.0

1

1.0

#

Rainfall Data

There must be NGAGES sets of rainfall data. Repeat lines from * to
*
for each gage inserting a variable number of TIME-DEPTH data pairs
(see example in User Manual).

#

* ALPHA-NUMERIC GAGE ID: 06/08/94 Zurkaya

#

GAGE NUM.	NUM. OF DATA PAIRS (ND)
-----	-----
1	13

1

13

#

There must be ND pairs of time-depth (T D) data: NOTE: The last
time
must be greater than TFIN (the total computational time).

#

TIME(min)	ACCUM. DEPTH(mm)
-----	-----
0	0.0
5	12.1
10	24.2
15	36.3
20	48.4
25	60.5
30	72.6
35	84.7
40	96.8
45	108.9
50	121.0
55	133.1
60	145.2

0

0.0

5

12.1

10

24.2

15

36.3

20

48.4

25

60.5

30

72.6

35

84.7

40

96.8

45

108.9

50

121.0

55

133.1

60

145.2

*

APPENDIX D

EXAMPLE OF CATCHMENT PARAMETER FILE FOR EUROSEM MODEL

MEUROSEM V. 3/93 Parameter Input File Dumburi Fako

#

***** S Y S T E M *****

* NELE	NPART	CLEN(M)	TFIN(min)	DELT(min)	THETA	TEMP
1	0	50.	15.	0.5	0.7	39

#

***** O P T I O N S *****

NTIME NEROS

2 2

#

**** C O M P U T A T I O N O R D E R ****

There must be NELE elements in the list. NLOG
must be sequential. ELEMENT NUM. need not be.

#

COMP. ORDER	ELEMENT
(NLOG)	NUM. (J)

-----	-----
1	1

#

***** E L E M E N T - W I S E I N F O ***

There must be NELE sets of the ELEMENT-WISE prompts and data
records; duplicate records from * to * for each element. The
elements may be entered in any order.

*

J	NU	NR	NL	NC1	NC2	NPRINT
1	0	0	0	0	0	1

-----	-----	-----	-----	-----	-----	-----
XL(M)	W(M)	S	ZR	ZL	BW(M)	MANN(Rilll)

Mann(IR)

50.0	50	0.005	0.0	0.0	0.0	0.06	0.06
------	----	-------	-----	-----	-----	------	------

-----	-----	-----	-----	-----	-----	-----	-----
FMIN(mm/h)	G(mm)	POR	ThI	ThMX	ROC	RECS(mm)	DINT(mm)
4.0	460.	0.40	0.02	0.38	0.0	10.0	0.0

-----	-----	-----	-----	-----	-----	-----	-----
DEPNO	RILLW(m)	RILLD(m)	ZLR	RS	ASR	RFR	SIR
0.0	0.00	0.00	0.0	0.	1.0	1.0	0.075

-----	-----	-----	-----	-----	-----	-----
COVER	SHAPE	PLANGLE	PLANTBASE	PLANTH(cm)	DERO(m)	ISTONE(+/-)
0.0	1	0.0	0.0	0.0	3.0	-1

-----	-----	-----	-----	-----	-----	-----	-----
D50(u)	EROD	SPLTEX	COH	RHOS	PAVE	SIGMAS	MCODE
125.0	1.6	2.0	5.0	2.65	0.0	0.00	1

APPENDIX E

DESCRIPTION OF THE BALANCE MODEL

Model structure

Figure E1 illustrates the various components and processes considered in the
BALANCE model.

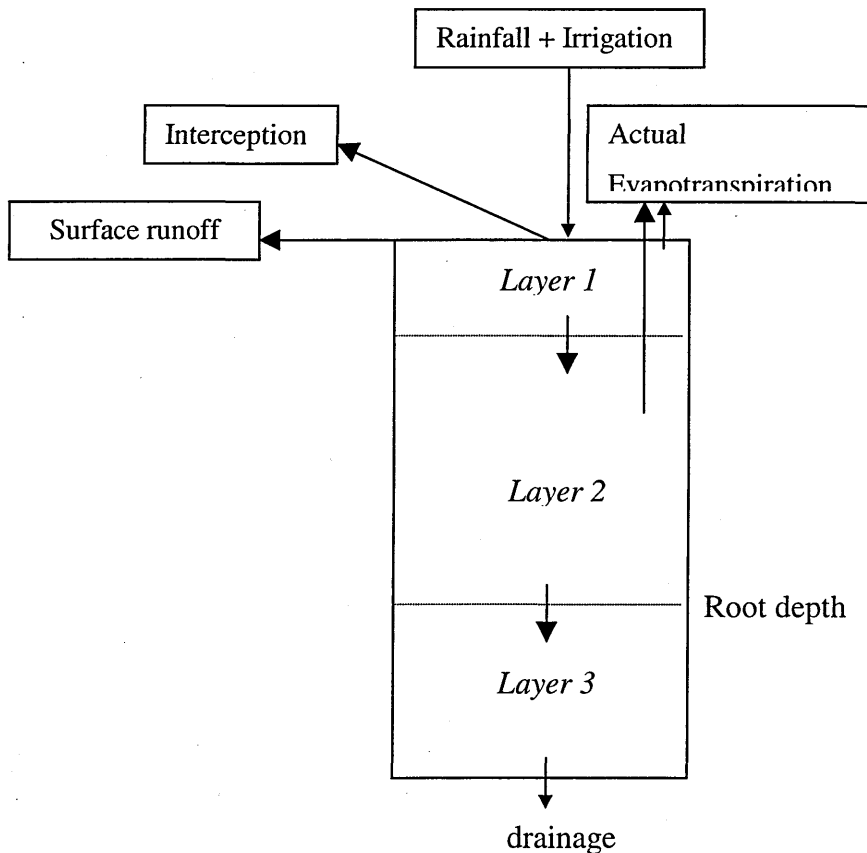


Figure E1: Outline of inputs and outputs to and from the soil layers in

BALANCE model (after Hess, 1994).

Soil profile is divided into three stores in the model. The first store consists of a top layer that is 15 cm from the surface, the second store is the root zone which depends on the root depth on each day, and the third store constitutes what is left of the soil

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profile beyond the root depth. This means that the third store will cease to exist when the root depth equals the profile depth.

Root depth is determined in the model for each day using the following Borg and Grimes (1986) empirical equation:

$$rd_i = rd_0 + \left[0.5 + 0.5 \times \sin \left(3.03 \times \left(\frac{i}{n} \right) - 1.47 \right) \right] \times (rd_{\max} - rd_0) \quad (1)$$

where,

rd_i = root depth on day i after planting (mm)

rd_0 = planting depth (mm)

i = number of days after planting

n = number of days after planting when maximum root depth is reached

rd_{\max} = maximum root depth (mm).

Ground cover fraction is determined by the crop cover fraction, mulch cover fraction and bare soil fraction. Development of the crop cover fraction and root depth follows the pattern illustrated by figure E2.

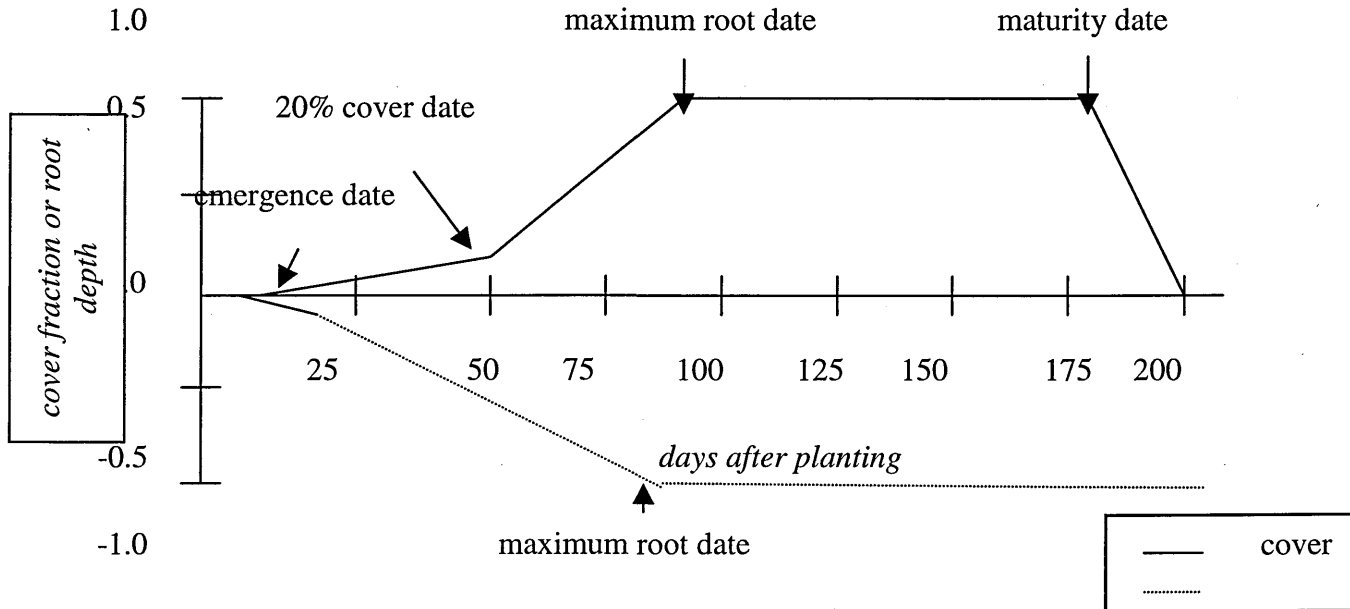


Figure E2: Crop cover and root depth development (after Hess, 1994).

The water balance components

The BALANCE model can provide estimates of the water balance components on daily basis. Below are descriptions of the methods used in BALANCE to estimate the five components.

Net Precipitation

The net or effective precipitation (P_e) is precipitation and/or irrigation less interception by the crop canopy. This input is estimated in BALANCE by the following formula;

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$$P_e = P - [a + b(P - a)] \times CC ; \text{ for } P > a \quad (2)$$

$$P_e = P ; \text{ for } P \leq a$$

where,

P = rainfall (mm)

CC = fraction of crop cover (-)

a = empirical constants (mm)

b = empirical constant (-).

Surface Runoff

BALANCE uses the SCS curve number method to estimate runoff on the surface of the soil. For a particular day, the curve number for average antecedent conditions and the relative saturation of the top 15 cm of the soil (Hawkins et al., 1985) is used by BALANCE to estimate the curve number to be used for calculating runoff.

Evapotranspiration

Actual evapotranspiration (ET_a) component of the water balance is estimated in BALANCE by summing up the actual soil evaporation, actual crop transpiration and evaporation from mulch cover (equation 3)

$$ET_a = Es_i + Ta_i + Em_i \quad (3)$$

where,

ET_{ai} = actual evapotranspiration on day i (mm)

Es_i = soil evaporation on day i (mm)

Em_i = evaporation from mulch cover on day i (mm)

Ta_i = actual transpiration on day i (mm)

1. Soil evaporation is estimated in BALANCE using the Ritchie (1972) method in which the evaporation takes place at constant rate during the first stage and at falling rate during the second stage. During the first stage, evaporation is taking place at the potential rate and it is assumed to be limited only by the supply of energy to the surface (Ritchie, 1972).

$$Es_i = Es_{oi} \quad (4)$$

Es_{oi} is estimated from:

$$Es_{oi} = ET_{oi} \times Bs_i \quad (5)$$

where,

Es_{oi} = potential soil evaporation (mm) on day i

Bs_i = bare soil fraction on day i (-)

ET_{oi} = reference crop evapotranspiration on day i. (mm)

During the second stage, evaporation takes place at a falling rate and water movement to the evaporating zone near the surface is controlled by the hydraulic properties of the soil and it is estimated from equation 6. Ritchie (1972) reported that, soil hydraulic conductivity is the property that mostly controls evaporation during this stage.

$$Es_i = \alpha t^{1/2} - \alpha(t-1)^{1/2}$$

(6)

where,

α = constant, (mmday^{-0.5}) and,

t = time in days since last rain in excess of potential soil evaporation.

2. Actual transpiration is assumed to occur at the potential rate whilst the root zone soil water deficit is less than the easily available water capacity of the root zone. This then reduces linearly to zero when the deficit reaches the total available water capacity.

$$T_{ai} = T_{oi} \quad (7)$$

Where,

$$T_{oi} = ET_{oi} \times CC_i \times KC_{max} \quad (8)$$

T_{oi} = Potential crop transpiration on day i (mm $_i$)

CC_i = crop cover fraction on day i , and

KC_{max} = ratio of potential transpiration to reference crop
evapotranspiration at maximum cover.

3. The evaporation from mulch cover is assumed to occur only on days when the mulch is wetted by rainfall or irrigation. In the model, the maximum storage allowed on the mulch surface is 2 mm and the conditions in table E1 hold when the model calculates evaporation from mulch.

Table E1: Conditions for calculating evaporation from mulch surface in**BALANCE model.**

<i>Condition</i>	<i>Em</i>
(rain +irrigation) = 0	0
(rain +irrigation) ≤ 2 mm	(rain+irrigation) × mulch cover fraction, or Eto × mulch cover; whichever is smaller
(rain + irrigation) > 2 mm	2.0 × mulch cover fraction or Eto×mulch cover fraction; whichever is smaller

Drainage

The model estimates drainage out of the soil profile in the following way: when the water content in a layer reaches saturation, any excess is assumed to drain immediately to the layer below it. However, if the water content is between field capacity and saturation, drainage is calculated from the soil hydraulic characteristics as described by equation 8:

$$dr = \tau(\theta - \theta_{fc}) \left(e^{(\theta - \theta_{fc})} - 1 \right) / \left(e^{(\theta_{sat} - \theta_{fc})} - 1 \right) \times 1000 \text{ mm} / m \quad (8)$$

where,

dr = drainage from layer in mm/m of layer thickness/day

τ = drainage constant

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θ = volume water fraction

θ_{fc} = volume water fraction at field capacity

θ_{sat} = volume water fraction at saturation.

Soil Water

BALANCE estimates the soil water content of each layer for every day by summing up the gains and losses as described in table E2.

Table E2: Gains and losses in the three layers of the soil profile as considered in the BALANCE model

Store	Gains	Losses
Layer 1	effective rainfall and irrigation	Soil evaporation, plant transpiration*, drainage and surface runoff.
Layer 2	drainage from layer 1	Plant transpiration* and drainage
Layer 3	drainage from layer 1 or 2	Drainage

**plant transpiration is calculated for each layer based on the proportion of the root in that layer to the rootzone.*

The water content of layer 1 is dependent on the root zone on that day, the water content of the layer the previous day, the amount of rainfall and/or irrigation added

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on that day, surface runoff, evapotranspiration and drainage out of the layer. This is mathematically represented as:

$$WC1_i = WC1_{i-1} + Pe_i - ETa_i - D1_i \quad (9)$$

where,

$WC1_i$ = water content of layer 1 on day i (mm)

$WC1_{i-1}$ = water content of layer 1 on the previous day (mm)

Ro = surface runoff (mm)

$ETa1_i$ = actual evapotranspiration from layer 1 on day i (mm)

$D1_i$ = drainage from layer 1 to layer 2 on day i (mm).

For layer 2, the water content is calculated from the water content of the previous day plus drainage from layer 1 and the extension of the root zone into layer 3, minus evapotranspiration and drainage from layer 2.

$$WC2_i = WC2_{i-1} + D1 + (rd_i - rd_{i-1}) \times 1000 \times \theta2_{i-1} - ETa2_i - D2_i \quad (10)$$

where,

$WC2_i$ = water content of layer 2 on day i (mm)

rd_{i-1} = root depth on day i-1 in m

$\theta2_{i-1}$ = volume water fraction of layer 2 on the previous day

$ETa2_i$ = actual evapotranspiration from layer 2 on day i (mm)

$D2_i$ = drainage from layer 2 to layer 3 on day i (mm).

The soil water content of layer 3 is calculated from the water content of the previous day plus drainage from the above layer minus drainage out of layer 3.

$$WC3_i = \theta3_{i-1} \times rd_i \times 1000 + D2_i - D3_i \quad (11)$$

where,

$WC3_i$ = water content of layer 3 on day i (mm)

$D3_i$ = drainage from layer 3 on day i (mm).

$\theta3_{i-1}$ = volume water fraction of layer 3 on the previous day